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VALIDATION OF AN EXPONENTIALLY DECREASING FAILURE RATE SOFTWARE RELIABILITY MODEL

THESIS

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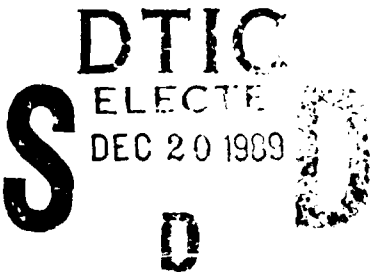

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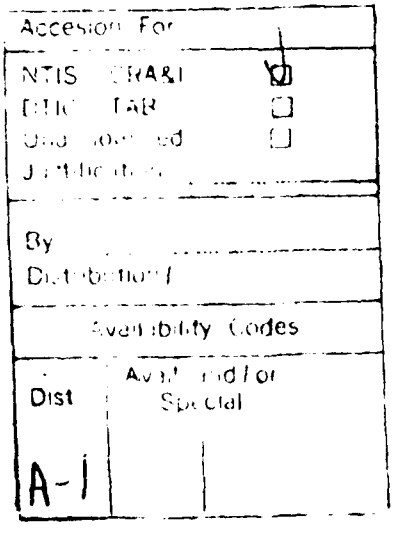

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THESIS

Presented to the Faculty of the School of Systems and Logistics of the Air Force Institute of Technology Air University In Partial Fulfillment of the Requirements for the Degree of Master of Science in Logistics Management

Charles J. Westgate, III, B.S., M.S.
Captain, USAF

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Preface

The purpose of this study was to determine the degree of validity of the Air Force Operational Test and Evaluation (AFOTEC) Software Reliability Estimation Model. The results of my research should help AFOTEC, the Air Force and all parties involved in buying or developing software. My intent in performing this research was to provide a tool that would be easy to use and have the degree of accuracy needed to make this model a valid tool.

In performing this research, I received assistance from several others. Without this help, I feel this document that you are now reading would not have been possible. First, I wish to thank Prof. Dan Ferens for his guidance and technical expertise. My wholehearted thanks to Lt Col Bruce Christensen for assistance in the area of statistics and to Capt Mike McPherson for the failure data and his knowledge of the AFOTEC Model. I must also express my appreciation to Dr. C. R. Penno for his assistance in the grammar and format of this document. Most of all, I wish to thank my wife Barbara and daughter Beth for their patience and understanding throughout these last fifteen months.

Charles J. Westgate, III

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Abstract

The purpose of this thesis was to determine the validity of a software reliability estimation model proposed by the Air Force Operational Test and Evaluation Center (AFOTEC). During the last forty years of the computer era, the demand for software has been growing at a rate of twelve percent per year; and about fifty percent of the total life cycle cost of a software system is attributed to software maintenance. It has also been shown that the cost of fixing a software fault increases dramatically as the life cycle progresses. It was statistics like those discussed above that prompted this research.

The research had these specific objectives: the first was ascertaining the soundness of the model's intrinsic logic. The second objective was to run the model with actual failure data to measure the validity and correlation of the data with the model. The final objective was to determine the assumptions required to operate the model.

The study found the AFOTEC Model to be invalid; however, improvements and assumptions could be easily applied to make the model a valid tool for estimating software reliability. Two improvements were proposed for the AFOTEC Model. First, the model should operate with the assumption that the data used in the model should be data obtained after software

testing has reached a steady state. The second recommendation was to modify the AFOTEC Model to emulate both the start-up phase and the steady state phase of testing.

VALIDATION OF AN EXPONENTIALLY DECREASING FAILURE RATE SOFTWARE RELIABILITY MODEL

I. Introduction

Overview

This chapter discusses the evolution of military weapon systems, and the growing role that software has in these systems. By addressing these issues, the need for reliable software will be revealed. The justification for the research has also been presented, and finally, the specific objectives, assumptions, and scope of the research has been established.

Definitions

The term reliability refers to the probability that a system will not fail within a given amount of time, and failure rate refers to the rate at which failures occur in a system at a specified time (24:80-84). For the purposes of this research, software reliability will be defined as "the probability of failure-free operation of a computer program for a specified time" (32:15). The software failure rate is defined as the rate at which software bugs or faults are discovered and is expressed as the number of failures per time (32:15-16). Finally, the term mean time between failures (MTBF) is the average time expected before the next fault is

detected. The MTBF can also be mathematically defined as the inverse of the failure rate (24:80-84). The terms reliability, mean time between failure (MTBF) and failure rate will be used as measures of software reliability.

Background

Throughout history, men have used mechanical/hardware weapon systems. From the first time that a prehistoric man used a rock as a weapon, we have been using hardware systems. However, it has been within the last 43 years that computers and software have come into existence (20:126), and only the last 37 years that computers have been commercially available (30:54). Thus, there has been much more research and knowledge in the topic of hardware and hardware reliability than in the area of software and software reliability.

The use of computers and software is increasing rapidly, however (26:41). For example, the first computer, the ENIAC, was built about 40 years ago and it was only capable of performing simple arithmetic functions at a speed of about 2.8 milliseconds (30:35). This computer weighed 30 tons (30:34) and occupied a space 100 feet long, 10 feet high and 3 feet deep (20:126). Today, a calculator can perform over 100 mathematical operations and can fit in the palm of a hand. Another example, the software in the B-1B Bomber performs up to one million calculations per second to keep the aircraft

flying (6:18), which is about one thousand times faster than the ENIAC computer. An example of the growing demand for software in military aircraft is shown in Figure 1.

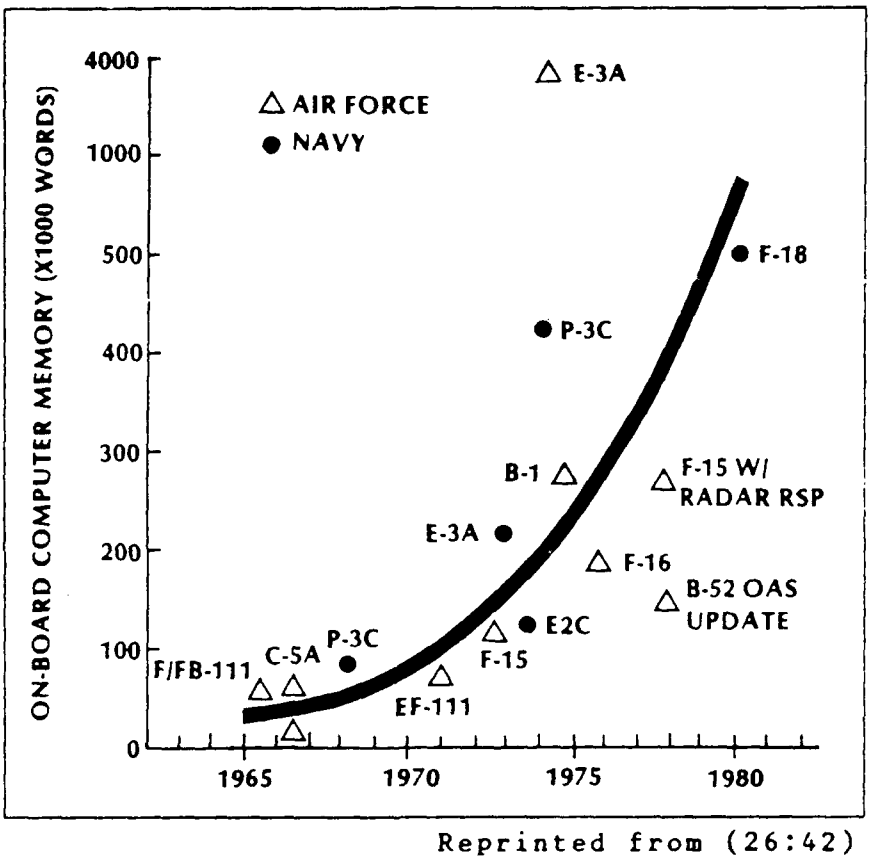

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Figure 1: Growth in Military Aircraft Software Requirements

This figure illustrates how the amount of software, measured in the number of lines of code, has increased in United States aircraft throughout the years. A similar example for space systems is shown in Figure 2.

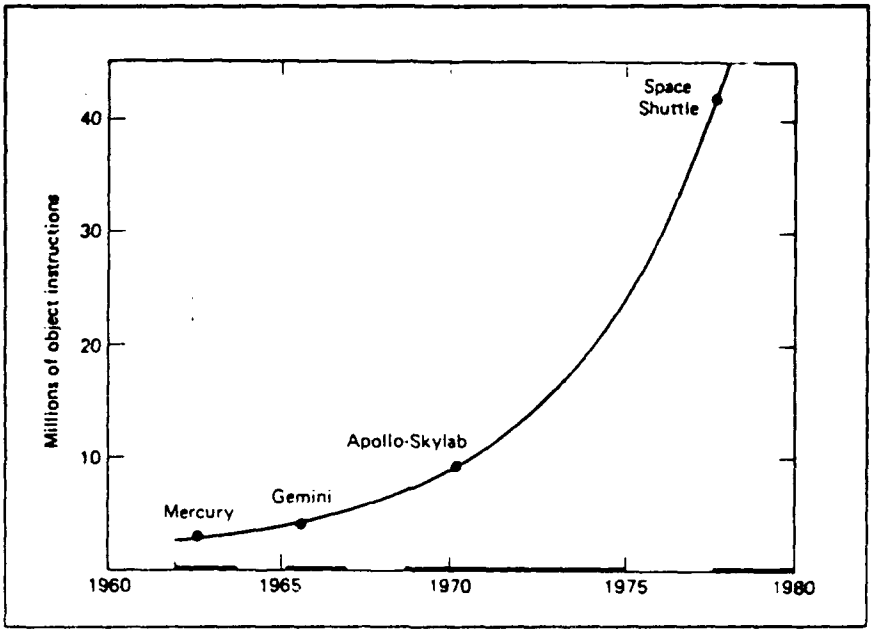

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Figure 2: Growth in Software Demand for Space Systems

Figure 3 represents the increase in software versus hardware in Air Force systems, measured as a percent of the total system cost. At this rate of growth, the Air Force cannot afford to overlook software (26:44).

Reliability has also grown in importance in the last few years, as the Air Force's Reliability and Maintainability Project, R & M 2000, demonstrates (10:1). By making systems more reliable, the systems should, by definition, fail less often; hence, less money should be spent maintaining these systems (31:15). In light of current budget cuts and the Graham-Rudman-Hollings Act, the Air Force has been required

to operate the same systems, but with a smaller budget (31:12).

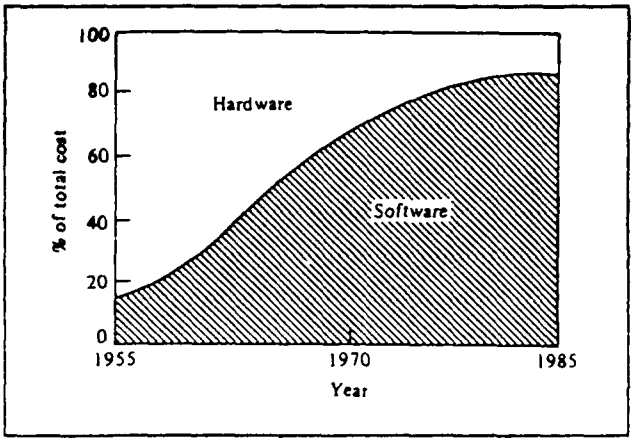

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Figure 3: Hardware and Software Cost Trend

Historically, about sixty percent of the total dollars spent on a weapon system is used for operating and maintaining the system (4); and, as shown in Figure 4, the cost of software maintenance is increasing as a percent of total system cost.

According to Halpin, 20 to 25 percent of all system failures are due to software faults (21:5.1). Glass states that 50 percent of the software life cycle cost is spent on software maintenance (Figure 5). Glass also claims, as shown in Figure 6, the cost to correct a software fault "increases dramatically as the software progresses through the life cycle" (18:11).

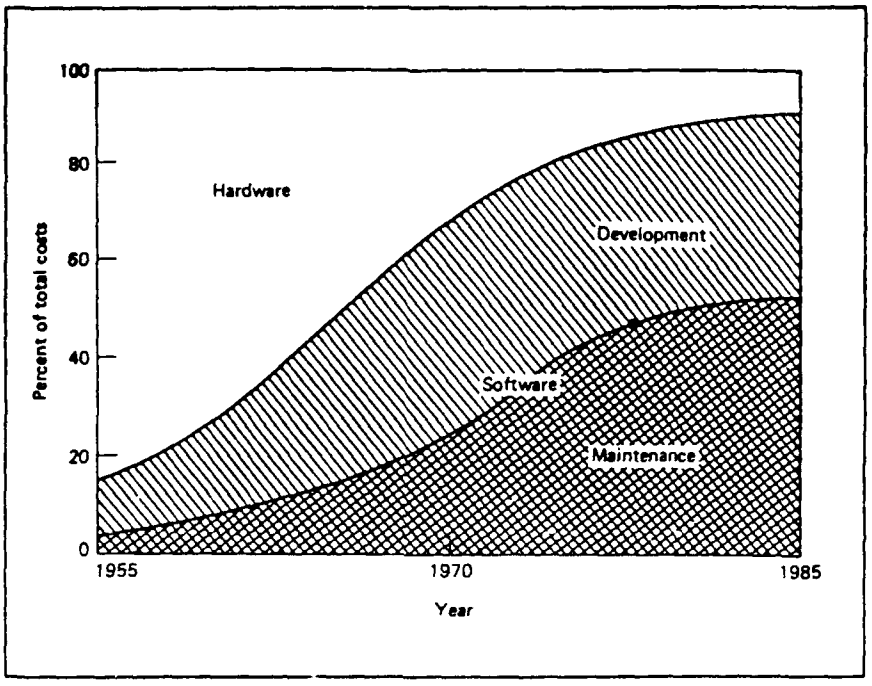

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Figure 4: Software Maintenance Cost Trend

Since the demand for software has been shown to be rapidly increasing along with the cost of maintaining software, money could be saved if software was produced reliably during the development phase. Hence, more reliable systems would help to cut costs. The cost savings is one of the reasons that the Air Force instituted the Reliability and Maintainability (R&M) 2000 Program (10:1).

Although the Air Force implemented R&M 2000 to cover both hardware and software, it does not provide much guidance on how to handle software reliability. The R&M 2000 Program Plan provides guidance on how reliability and maintainability

programs should be developed and managed; however, the document does not mention how software reliability should be handled (25:356).

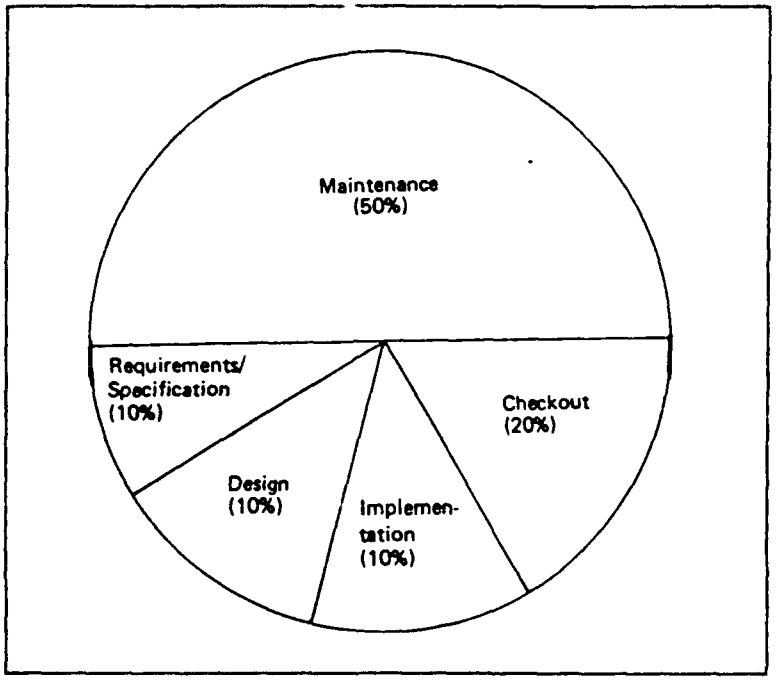

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Figure 5: Software Life Cycle Cost per Phase

The only guidance given by the Air Force can be found in Air Force Regulation (AFR) 800-18, which only directs: "Integrate the development of reliable software into the overall system development and acquisition program" (9:3). No other information or direction is given on how to develop reliable software or how to measure the reliability. In fact, a military standard directs that, when calculating system

reliability, the software reliability should be assumed to be completely reliable (11:100-3). Thus, it is important to research the area of measuring the reliability of software and the techniques of developing reliable software.

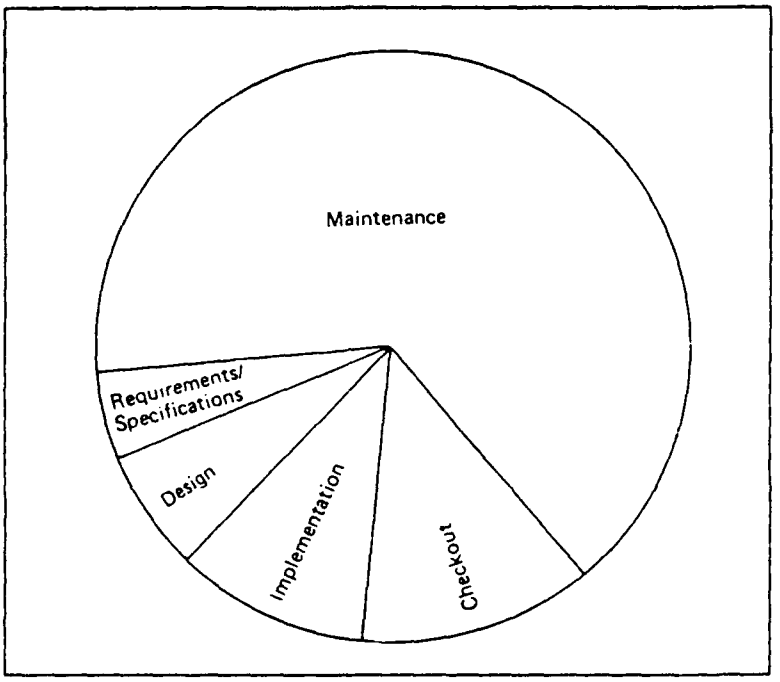

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Figure 6: Fix Cost per Error per Phase

General Issue

The general question examined in this thesis was how to improve the reliability of the software that accounts for a major portion of the United States Air Force's weapon systems. The answer to this question will not only increase the reliability of the software or computer program in these

weapon systems, but will also improve the reliability of the entire system.

Research Question

In order to improve the reliability of software, a method should first be developed to measure the reliability. This measurement is required to determine if a technique for improving reliability has in fact made an improvement. After a system of measurement has been developed, proposed reliability improvement techniques can be compared using the measurement system. The comparisons can be used to judge which improvement technique will, in fact, result in improvements; and which techniques will provide the best results. For example, a reliability model could be used to compare various software fault tolerance techniques.

The research question that has been answered in this thesis is how to quantitatively measure the reliability of software. To answer this question, it was first necessary to decide if a new model should be developed and validated to measure software reliability or if an existing model could be chosen to be validated. After researching the current literature on the topic of software reliability and contacting organizations that have ongoing research in the area, it was determined that several models are already in existence. Hence, it was decided to choose an existing model. Therefore, the specific research question is: What is the validity of the software

reliability model that has been developed by the Air Force Operational Test and Evaluation Center (AFOTEC) to measure the reliability of software during the operational test and evaluation (OT&E) phase of a development program?

Research Objectives

To determine if the AFOTEC Model is valid, three objectives had to be met. The first objective was to ascertain if the theory behind the model is sound and, if so, to what extent. The second objective was to run the model with existing data to evaluate how well it predicted reliability. The final objective was to conclude under what assumptions the model was valid and to comment on the applicability of the model during other phases of the development cycle.

Justification

Since the model chosen to be validated was developed by the Air Force Operational Test and Evaluation Center, they have sponsored this research realizing that the findings could help standardize the way in which both AFOTEC and the Air Force define and measure software reliability (22). The results of this research can also be applied to Air Force acquisition contracts as a method of determining the degree to which the system under contract meets a given reliability requirement in the specification, and to determine if the software meets the reliability requirements of the operational commands.

Scope and Limitations

The scope of this research is limited to the validation of the AFOTEC Model during the operational test and evaluation phase; however, generalizations will be made as to the model's validity during other phases of the acquisition cycle. Another limitation to this research is in the use of available data. Enough time is not available to develop software and collect a primary source of data; therefore, the analysis has been limited to the use of secondary or already existing databases. This data has been obtained from Rome Air Development Center (RADC), AFOTEC, and the Aeronautical Systems Division (ASD) Information Center (INFOCEN).

Summary

This chapter discussed the importance of reliable software and how it can affect the maintenance and budgetary requirements of the Air Force. It has also been pointed out that before developing reliable software, a method for measuring software reliability should first be developed.

Chapter II contains a summary of the current literature and research in the areas of software reliability, fault tolerance and reliability improvement techniques, current Air Force guidance, and statistical model validation techniques.

II. Literature Review

Introduction

This chapter is a review of literature that deals with the topics of reliability and fault tolerance of software. It also covers current Air Force guidance for managing software reliability and techniques of validating statistical models.

Scope

The literature search was limited to the last fifteen years because, according to Dunham, research in the area of software reliability did not begin until 1972 (15:111). The search concentrated on military applications, although it was not confined to this area. Literature searches were performed through the National Aeronautics and Space Administration (NASA), Defense Technical Information Center (DTIC), DIALOG, and RADC literary databases.

General Model Types

Currently, several types of models exist that are capable of estimating the reliability of software or counting the number of errors in a program. The five general types of models are mean time between failure, error counting, error seeding, metrics, and input domain (16:1-6). However, they are not all useful for all stages in the software life cycle, and they have not been proven to be valid models.

Error Counting Models. Error counting models or exponentially decreasing failure rate models usually assume a Poisson distribution for the number of errors remaining at some point in time (16:2). This type of model is useful during the final stages of software development, such as integration and test, acceptance test, and operational use (19:1418-1420). Estimating the input parameters for these models, however, can be difficult. A typical parameter which must be estimated is the initial number of errors in the software; however, error seeding models can estimate this number.

Error Seeding Models. The error seeding models require a programmer to insert faults into the software, and then an independent programmer counts the number of errors that he or she finds. The model uses a ratio of the number of seeded errors detected to the number of non-seeded errors. The ratio is used to estimate the initial number of errors in the software (16:2). This model can be useful during the unit test phase or when used to estimate the input parameter of another model (19:1419).

Mean Time Between Failure Models. The mean time between failure (MTBF) models are very similar to the error counting models. The MTBF models calculate the estimated time until the next error will be detected, as compared to the error counting models that estimate the number of errors detected by some point in time (16:3).

Metrics Models. Metrics models use qualitative inputs to a model to obtain quantitative values of the software quality. Examples of the inputs include complexity of the software, programming language used, experience of the programmer, and programming structure. All of these inputs require a subjective evaluation of parameters that are difficult to quantify. Bruce Brocka suggests software should not be evaluated for reliability; rather, it should be measured for maturity and utility (8:28). The use of a Metrics model is one such method of measuring maturity and utility.

Input Domain Models. Input domain models operate on a ratio principle similar to the fault seeding models. Input domain models use a set of test cases or input parameters that are generated to represent the expected operating environment. The reliability is assumed to be proportional to the ratio of the number of cases that cause an error to the total number of cases generated (19:1416).

Current Software Reliability Models

Currently, there are approximately forty models that have been developed to estimate software reliability (1:94). The following section contains a brief description of some of the more popular models that have been developed to estimate software reliability.

Schick - Wolverton Linear Model. The Schick - Wolverton Model is an example of a time between failure model because

it calculates a failure rate based on the time between the ith and the (i-1)st failure. This failure rate is expressed by a Rayleigh distribution and can be expressed by:

$$h(t_i) = K[E_0 - (i-1)]x_i \quad (1)$$

and the reliability is defined as:

$$R(t_i) = \exp[-h(t_i)*t/2] \quad (2)$$

where

K = constant of proportionality
E_0 = initial number of errors in the program
x_i = debugging time between the (i-1)st and ith error

The equations above assume that the time required to remove faults is negligible and that new faults are not introduced during debugging (14:118-124).

Jelinski - Moranda Model. This model was developed in 1972, and is another example of a time between failure model (19:1413). The Jelinski - Moranda Model is similar in form to the Schick - Wolverton Model; however, the failure rate is distributed exponentially and is only proportional to the number of faults remaining at some time. The failure rate is defined as:

$$h(t_i) = K[E_0 - (i - 1)] \quad (3)$$

and the reliability is given by:

$$R(t_i) = \exp[-h(t_i) * t_i] \quad (4)$$

The Jelinski - Moranda Model has the same assumptions as discussed above (14:118-123).

Shooman Model. Shooman's failure count model was also developed in 1972, and it assumes the failure rate to be

proportional to the number of faults per machine language instruction (35:369). Shooman defines the failure rate to be:

$$h(t) = K[(N/I) - n] \quad (5)$$

where

N = initial number of errors
I = total number of machine language instructions
n = total number of faults corrected by time, t

The two unknowns in the Shooman Model, N and K, must be determined before this model can be used. A technique known as moment matching can be used to provide an estimate of these parameters. Dhillon and Singh's text provides a solution for these parameters as well as a reference on the moment matching technique (14:121-122).

Goel - Okumoto Nonhomogeneous Poisson Model. The Goel - Okumoto Model represents the failure rate as exponentially decreasing. For this model, the cumulative number of faults detected by time, t is given by:

$$M(t) = a[1 - \exp(-bt)] \quad (6)$$

therefore, by taking the derivative, the failure rate is determined by differentiating equation (6):

$$M'(t) = ab[\exp(-bt)] \quad (7)$$

where

a = total expected number of software faults
b = fault detection rate per fault
t = cumulative time on test

The "a" and "b" can be estimated by a maximum likelihood function calculated using sample failure data (19:1415).

Musa Execution Time Model. The Musa Model was developed in 1975 and is another example of a failure counting model. The model assumes the failure rate to be proportional to the number of faults remaining in the program after t units of CPU time. The failure rate is expressed by:

$$h(t) = Kf(N - n) \tag{8}$$

where

K = constant of proportionality
N = initial number of faults
n = number of faults corrected by time, t
f = E/I
E = average instruction execution rate
I = number of instructions in the program

Musa's model uses the actual Computer Processing Unit (CPU) execution time rather than the amount of time on test; therefore, the estimated reliability should not be artificially increased due to an increase in testing time (32:285-288).

AFOTEC Model. The following information dealing with the AFOTEC Model is taken from an unpublished paper by Wiltse, McPherson and Holmquist of AFOTEC titled "Predicting System Reliability: Software and Hardware" (27:1-15). A copy of this document can be found in Appendix C.

The purpose of the AFOTEC Model is to provide a practical method of combining hardware and software reliability data during Operational Test and Evaluation (OT&E), in order to estimate the system reliability. Prior to using this model, AFOTEC considered software to be 100% reliable.

Although AFOTEC's model was derived from the Goel - Okumoto Failure Count Model, there are two major differences between the two models. First, the AFOTEC Model uses calendar dates (day-month-year) rather than execution or testing time. The use of calendar time has been demonstrated by Musa (32:54-57) to be a valid method of modeling software faults. Second, AFOTEC added an imperfect debugging model that represents a pessimistic bound on the reliability.

When AFOTEC is performing tests on software, they record the following information for each software fault discovered: the date fault was discovered, a problem number, the affected computer program configuration item (CPCI), a DOD severity code (See Table I), a description of the problem, and the date the fault was fixed. However, the AFOTEC Software Reliability Model only uses the date the fault was discovered and the cumulative number of faults discovered. The AFOTEC Model also limits the data to those faults with an associated DOD severity code of 1 or 2.

AFOTEC's basic model has the same form as the Goel - Okumoto Model shown above in equations (6) and (7). This basic model is used to estimate the "a" and "b" parameters from the sample failure data. AFOTEC's model operates under assumption that at the beginning of testing, faults will be discovered at fast rate; however, as fewer faults remain, the slower they will be discovered. Figure 7 shows a graphical representation of what the model expects.

Table I: DOD Severity Codes

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Severity Level	Severity	Description
1	System Abort.	A software of firmware problem that results in a system abort.
2	System Degraded. No Work-around.	A software of firmware problem that severely degrades the system and no alternative work-around exists (program restarts not acceptable).
3	System Degraded. Work-around.	A software or firmware problem that severely degrades the system and there exists an alternative work-around (i.e. system rerouting through operator switchology; no program restarts).
4	Software Problem. System not Degraded.	An indicated software of firmware problem that does not severely degrade the system or any essential system function.
5	Minor Fault.	All other minor deficiencies of non-functional faults.

Although most models assume the failure rate to be decreasing (Figure 7), some authors do not always agree. Yamada and Osaki believe the failure rate could exhibit an S-shape (Figure 8), thus the failure rate initially increases and eventually decreases (36:1433). They believe the S-shape is due to one of two reasons. First, the process of isolating a fault could cause the initial low failure rate. Second, failure detection could be dependent on the number of errors already detected; therefore, the more failures are detected, then the more undetected failures become detected (36:1433).

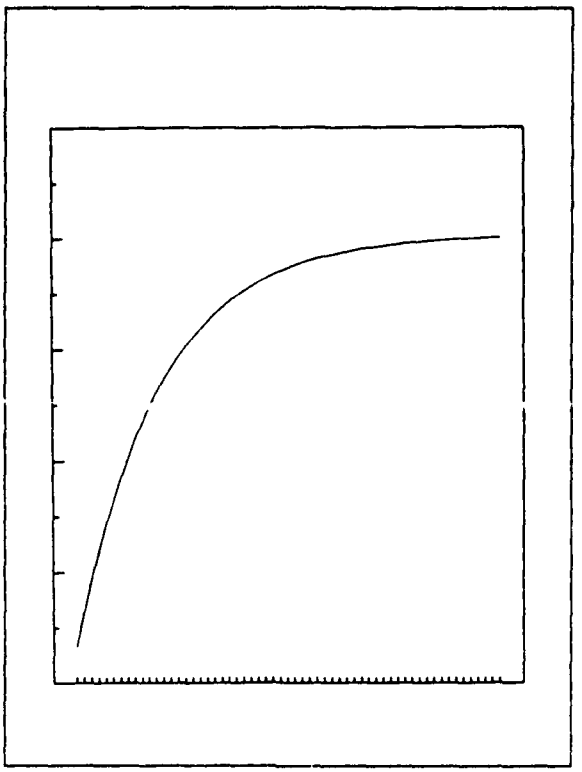

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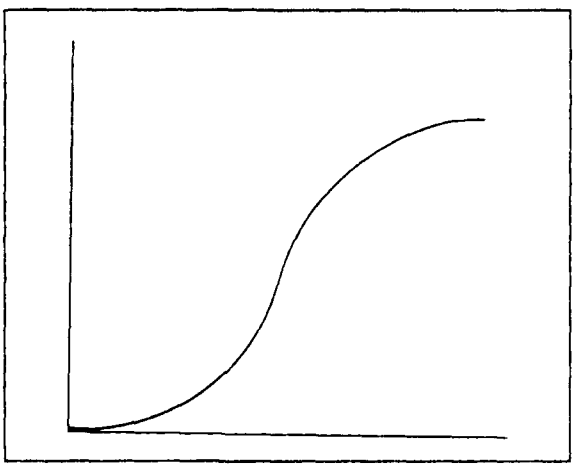
Figure 7: AFOTEC Model of Software Faults



Adapted from (36:1433)

Figure 8: S-Shaped Software Fault Model

McPherson does not agree with Yamada and Osaki, and states that the S-shaped data could be due to slow testing initially, or due to systems with higher priorities taking test time from the system (28).

AFOTEC's Imperfect Debugging Model provides a pessimistic prediction of the number of software faults based on the assumption that faults may be introduced into the program during debugging. This model has the following form:

$$M(t) = a'[1 - \exp(-bt)] \qquad (9)$$

and

$$M'(t) = a'b\,[\exp(-bt)] \qquad (10)$$

where

$M(t)$ = cumulative number of faults
$M'(t)$ = failure rate
a' = a/B

In this model, the value of B is defined by Musa as 0.96, and "a" and "b" are the same as defined above.

After the optimistic and pessimistic failure rates have been calculated using the Basic and Imperfect Debugging Models, respectively, the software mean time between failures are estimated by calculating the inverse of the failure rates. Now, a system MTBF is calculated as follows:

$$MTBF_{SYS} = 1 \,/\, \{\, [1/MTBF_{HW}] + [1/MTBF_{SW}] \,\} \qquad (11)$$

where

$MTBF_{SYS}$ = MTBF of the system
$MTBF_{HW}$ = MTBF of the hardware
$MTBF_{SW}$ = MTBF of the software

AFOTEC has also developed a model to estimate reliability of software programs undergoing major enhancements or modifications. This model represents the failure rate as being proportional to the amount of code being modified. This model, however, will not be studied in this thesis.

Fault Tolerance

Fault tolerance is closely associated with software reliability. The techniques used in fault tolerance have the goal of reducing the probability that a software program will produce incorrect results or will fail. These methods operate by checking the output of a program or by performing alternate routines if an error occurs. Hence, the outcome of fault tolerance is to improve the reliability of the software. Sabotage and software viruses are growing problems today, according to Boorman et al. (7:75-78), and fault tolerance could also help to reduce these problems.

Several techniques of fault tolerance are currently in use. These include active and passive redundancy, exception handling, graceful degradation, factored programming, structured programming languages, and combinations of any of the above methods (17:1). The main problem that exists with using any of the fault tolerance methods is the cost that is associated with implementing them. A trade-off must be made between the amount of dollars spent on fault tolerance and the level of reliability that the user is willing to accept. For

example, the manufacturer of video games would not be willing to spend the same amount on fault tolerance as the developers of the space shuttle or fighter aircraft.

Active redundancy involves the use of independently coded versions of the same program. The programs are then run simultaneously and the outputs are compared. If three or more versions are used and one version's output does not match the others, then it is considered to be incorrect. The output that is given by a majority of the versions is considered to be the correct answer, and then execution of the program continues. This technique is also called "N-Version Programming" (17:2).

Passive redundancy also involves the use of independently coded versions of the same program; however, in this technique the computer only executes one version of the program at a time. The second version is run only if an error is detected in the first version. This technique is known as the "Recovery Block Method" (17:3).

According to Ferens, exception handling requires only one version of a program, and uses subroutines coded into the program that instruct the program concerning what to do if it encounters an error (17:3).

Graceful degradation and factored programming are examples of combinations of the above methods. Graceful degradation is similar to the recovery block method except that the alternate versions of the program are simpler and less

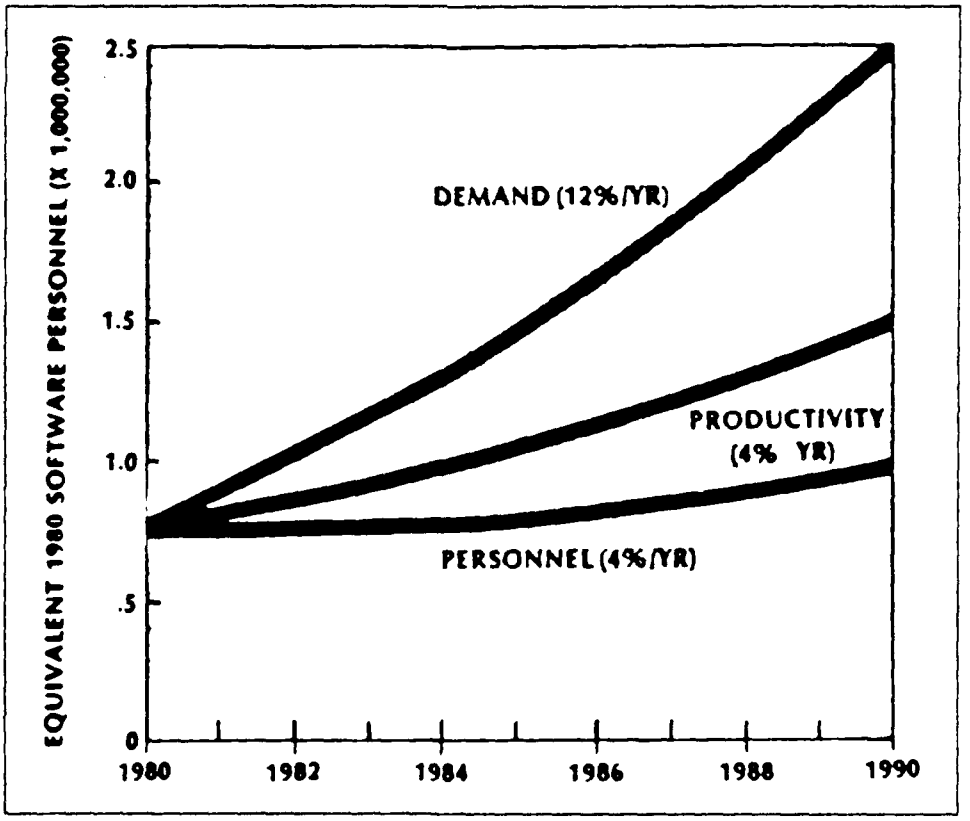
complex. Therefore, as the program moves to alternate versions, the chance of encountering an error decreases, but at the loss of some extra functions (17:4). With factored programming, according to Ferens, "the overall result is a weighted sum of the individual program results, with more weight given to the simpler, more reliable program" (17:4).

The final technique of fault tolerance to be discussed is structured program languages. Currently, the Department of Defense (DOD) is working towards developing a standardized higher order language (HOL) that will be easily understood and will have built-in fault tolerance, and ease of error detection and debugging. This language, Ada, will be required in all DOD software development programs. One benefit of using Ada is to reduce the number of lines of code needed to write a program. For instance, a program that had 300,000 lines of COBOL code was rewritten using only 30,000 lines of Ada code (25:360). This illustration shows how developers can benefit from using Ada.

According to Lipow et al., the United States spent $11 billion on software in 1985 and the author projects that this cost would more than double by 1990, to $25 billion (25:356). Figure 9 depicts the demand for software as increasing at a rate of 12 percent per year; but the availability of personnel and productivity is only increasing at a rate of 4 percent per year. Lipow claims that this trend would result in a shortage of 140,000 programers by 1990 (25:356). At these rates it is

apparent that improvements in the area of software development will be needed; Ada and other fault tolerance methods could be the answer.

Although fault tolerance seems to have many advantages, Perens states that several organizations are still skeptical. The producers of the Airbus A310 felt that although 2-Version programming was useful and effective, 3-Version programming is not. The Airbus personnel believed that extensively testing a single version would produce the same reliability as 3-Version programming, but at a lower cost (17:5).



Adapted from (26:43)

Figure 9: Trend in Software Personnel

Another example of the skepticism of fault tolerance was found in the Canadian Government. "A spokesman for the Atomic Energy of Canada project thought that dissimilar software would not have been used if the regulations did not require it; that it was, in effect, [is] counterproductive to software reliability" (17:6).

Application and Guidance

The next topic examined was current guidance and direction on the development of reliable software, software reliability estimates, and fault tolerant software. This research was used to determine where shortfalls lie in the guidance, and then recommend that changes, additions or new manuals be written to reflect the application of the thesis results.

At this time, the Air Force has not given guidance on how to develop reliable software or how to estimate software reliability; however, the DOD is conducting several projects to help solve the problem. Lipow et al. mention several of these projects, such as Software Technology for Adaptable Reliable Systems (STARS), the Software Engineering Institute (SEI), Ada Joint Program Office (AJPO), an Ada Hotline, and DOD Software Reliability and Maintainability Panel. This DOD panel is scheduled to publish a manual for software test and evaluation (25:356).

The Air Force Systems Command (AFSC) published two pamphlets, one on software quality (2) and one on management

indicators (3); however, these documents only give clues that might indicate poor quality or management of software. Also, these documents are only pamphlets and not regulations; therefore, members of AFSC are not required to apply the information given in the documents.

The Department of Defense has only published two directives for software management (12) and software quality (13). These directives are a step in the right direction; however, they only address the management of software development and not the actual methods required to develop reliable software or estimate its reliability.

Validation Methods

Currently, the main methods for validating a model are through the use of statistics and regression techniques. Regression analysis fits a line, in the form of the model, through the given data and then uses a correlation coefficient to measure how closely the data fits this line (33:301-331). If the correlation is equal to $\pm$ 1, then the data fits the model exactly. The closer the correlation is to zero, the less likely the data fits the model (29:213). It is also generally accepted that the sample size for statistical test should be at least thirty data points (33:113).

Another method of validating a model is to evaluate the estimate of the model parameters. Confidence intervals or statistical tests are usually used to evaluate parameters

(33:339-349). When using a statistical test, the data is used to test the probability of the parameter equaling zero. The model is assumed to be invalid if the statistical test finds a probability of the parameter equalling zero. Similarly, if a confidence interval encloses the number zero, then the model is assumed to be invalid (33:39-349).

A final method of validating a model is to evaluate the residuals or errors in the model. This test can be performed by calculating the mean and standard deviation of residuals and using a confidence interval or statistical to determine if the mean is equal to zero. For the model to be valid, the mean should have a probability of being zero (33:581-598).

For models that are used for predictions, as in the case of the reliability model, the next step is to determine the level of confidence in the prediction that the model generates. This is done with statistical confidence intervals on the prediction or by evaluating the variation in the error of the predictions (33:356-362). A confidence interval simply provides the range of values in which there is a given probability of this interval enclosing the actual value of interest (33:126-129).

Another method of validating the predictive capability of a model is to split the data into to parts. The first part is used to build a model. The second part is used to compare with the model's predictions at the respective data points. The percentage of data required to build the model should be

at least fifty percent, to ensure the most accurate model possible, yet allowing for remaining data to test the accuracy of the predictions (33:544). In this thesis, the data was arbitrarily divided with eighty percent used to validate the model, and twenty percent used to test the predictive capability of the model.

Conclusions

The reliability of software is a problem that the United States Air Force must face. Due to the growth of software in weapon systems and Air Force dependency on software, it is important that the software be reliable and dependable. The Air Force does not have the manpower, dollars, resources or experience to efficiently maintain all of the software that will be in its systems. To correct the problem, steps must be taken to improve software reliability. To do this more effectively, the Air Force will need a tool for measuring the reliability of the software.

If methods for measuring software are found to be valid, improvements can be made using fault tolerance techniques, and the progress measured using software reliability models.

The military and industry have developed several methods for estimating reliability and making software fault tolerant; however, the validity of the methods has not been proven, and many experts in the field doubt their usefulness. These methods must be evaluated for applicability, and if they are

not proven useful, then new methods must be developed. Equally important, regulations and guidance must be developed and published. These documents are needed to give, to those who are developing and managing software, common direction on how to use the reliability and fault tolerance tools that have been developed.

III. Methodology

Introduction

In general, statistical modeling was used to determine if the AFOTEC Software Reliability Model was valid and if the model can be generalized for other applications. The literature review in the previous chapter discussed the theory and intrinsic assumptions of some of the more common software reliability models, along with methods of assessing the validity of such models.

This chapter discusses the actual methodology that has been used in performing the validation of the AFOTEC Software Reliability Model. The discussion has been divided into three main sections: model feasibility, model validation, and model assumptions.

Model Feasibility

The first step was to study the modeling of software reliability that is currently being performed by industry, academia, and the military. This has been documented in the preceding chapter as a result of a literature search done through DTIC literature searches and contacting software associated organizations and institutes such as the Software Engineering Institute, the Air Force R&M 2000 program office, and Rome Air Development Center. This research resulted in a better understanding of modeling and the nature of software reliability.

Next, the AFOTEC Model was compared to other existing models, based on the information gathered in the literature review, to decide if the intrinsic assumptions are sound. The comparison also identified the relative ease of executing the model, thus determining if the AFOTEC Model is suitable for implementation in the Air Force.

Model Validation

The second step was to determine the validity of the model. This was accomplished by first collecting software reliability data on several software programs. The data was obtained from AFOTEC, Rome Air Development Center, and the Aeronautical Systems Division (ASD) Information Center (INFOCEN) databases. The data was then examined to determine if it was appropriate, as required by the model.

Next, the data was divided into two parts. The first eighty percent of the data was analyzed using the Statistical Analysis System (SAS) on the Air Force Institute of Technology (AFIT) main frame VAX computer to determine the correlation of the data to the model. The remaining twenty percent was used later to test the predictive nature of the model. The "PROC NLIN" function of SAS was used to perform a nonlinear regression of the data (34:575-606). The nonlinear technique was required because the AFOTEC Model is not a linear equation, nor can it be converted to a linear equation. The nonlinear regression method used by SAS performs iterative

calculations to find the best fit of the data with the model. Once the best fit is determined, PROC NLIN estimates the model parameters.

To judge the validity of the model, four tests were designed. The criteria established for passing the test were set arbitrarily, as is in most statistical tests. Since most statistical measures do not present right or wrong, but only degrees of better or worse, the criteria are set arbitrarily to achieve a desired accuracy. If more accuracy is required, future researchers may duplicate the experiment described in this chapter with tighter test criteria. The first test was to measure the coefficient of determination (R^2). The coefficient of determination is simply the square of the correlation; hence, it has similar properties. The coefficient of determination is a measure of goodness of fit, and a value of 1.0 means a perfect fit and 0.0 indicates the worse possible fit. According to Kvalseth, the coefficient of determination is an acceptable method of determining correlation for a nonlinear equation (23:279-285), and is calculated by:

$$R^2 = 1 - (SSE/SST) \qquad (12)$$

where

SSE = sum of square residuals
SST = corrected total sum of squares

Both SSE and SST can be found on the SAS printout. Each set of data tested was required to have a coefficient of

determination greater than 0.75 and the average coefficient greater than 0.85.

The next test was to evaluate the confidence interval on the parameter estimates, as calculated by SAS. For the model to be valid, the 95% confidence interval should not encompass the value of zero. If zero is enclosed by the interval, it would indicate that there was a probability of the parameter also being zero. Either parameter equaling zero would indicate no faults were in the software; however, the data would indicate otherwise. The 95% confidence interval can be defined as the interval that has a 95% probability of the including the actual value of the parameter.

The third test was to examine the residuals or error in the model. The residuals are defined by calculating the difference between the actual data point and the point estimated by the model. For the model to be valid, the mean of the residuals is expected to be zero. In other words, on the average there should be no error in the model. The criteria set for this test is to have a mean less than $\pm$ 10 faults. When examining the error, the spread of the residuals, or standard deviation, is also important. The standard deviation of residuals is calculated by:

$$s_e = (MSE)^{0.5} \qquad (13)$$

where MSE is the mean squared residual found on the SAS printout. The standard deviation of residuals will not have a specific criteria test for validity; rather, the standard

deviations will only receive comments on their values as being high, low, or acceptable.

The last test was to view the shape of the data plot, with the date being on the independent axis and cumulative number of faults on the dependent axis. If the graph increases sharply and then levels off, as shown previously in Figure 7, then the model may be valid. This is a subjective test; therefore, the results are not used to prove or disprove the validity. This test is used primarily to get a first impression of the expected results. A test of this sort is often helpful in determining if the results are logical.

The final objective in validating the model was to determine the validity of its predictive capability. This assessment was done by comparing the remaining twenty percent of the data to the values predicted by the model. The predictions were calculated by SAS at each point respective to the actual data. The validity was then checked using a test similar to the residual tests stated above. Again, the mean residual of the predictions were expected to be within $\pm$ 10 faults, and comments were made on the standard deviations.

Model Assumptions

The third step was to review the assumptions under which the model appears to be valid. This was done by first finding discrepancies in the model, as compared to the actual data.

The discrepancies were then studied to help establish what assumptions must be made in order for the model to remain valid. Another method used to determine the assumptions was to evaluate various types and categories of data, such as aircraft, space, test equipment, and main frame software to ascertain which applications best fit the model.

The last technique was to return to the literature and observe what assumptions are typically made in software reliability models, and which are appropriate to the AFOTEC Model.

Summary

The methodology that has been highlighted in this chapter consists mainly of statistical methods that have been discussed in Chapter II - Literature Review. The steps provided in this chapter, along with data provided in Appendix F, should be sufficient for future researchers to recreate the experiments performed in this document. This methodology was used in deriving the results and conclusions found in the remaining chapters.

IV. Findings and Analysis

Introduction

This chapter discusses the results of the research conducted under the methodology described in Chapter III - Methodology and presents the information required to answer the research question posed in Chapter I - Introduction. The format for this chapter will follow the outline in Chapter III - Methodology, and the results of each step in the research methodology will be discussed in detail in each of the following sections.

In general, the results of the research do not support the validity of the software reliability model; however, suggested causes for the invalid finding and recommended improvements to the model will be discussed in the following chapter and appendices.

Model Feasibility

The first step in determining the validity of the model was to determine the feasibility of the model. This was done by performing a review of literature on the subject of software reliability models as discussed in Chapter II - Literature Review. The AFOTEC Model was compared to the existing theoretical models found in the literature to ascertain if it is sound and logical.

From the literature, it was apparent that the AFOTEC Model is similar to the Goel and Okumoto Nonhomogeneous Poisson

Model (19:1415) and also has a form similar to the Jelinski and Moranda (14:118-123), and Schick -Wolverton Models (14:118-124). The AFOTEC Model also represents a decreasing failure rate, which is common in most software reliability models.

The Basic AFOTEC Model has the exact form as the Goel and Okumoto Model, Equation (6), but has one difference: The Basic AFOTEC Model uses calendar time rather than execution or test time. As pointed out in Chapter II, Musa has proven this to be a valid technique (32:54-57). Thus, it is assumed that the model can be considered logical and based on sound theory.

Model Validation

To validate the model, data was collected and statistical measures of the data versus the model were calculated. The data was collected from AFOTEC, Rome Air Development Center, and the Aeronautical Systems Division INFOCEN; and was then examined to determine if it was appropriate for use with the model. The examination included studying data fields included in the databases, checking for outlier or unreasonable values, checking for consistency in units, and when possible, examining the data collection techniques.

Obstacles were encountered in all of the databases except the AFOTEC database. The major problem with the other databases was the lack of required data fields. The AFOTEC

Software Reliability Model requires data fields on the calendar date of a software fault, and an associated severity code for each fault, which were not present in the other data bases. Another problem encountered was that faults were recorded by computer central processing unit (CPU) execution time rather than calendar time.

Some problems were also discovered in the AFOTEC databases. AFOTEC provided data for eleven systems that it had tested. These systems included space, aircraft and communications systems. Since five of the databases had fewer than 30 data points, only six of the databases could be used for this research.

A major concern with using the AFOTEC database was to determine if the data is biased. If the data used to develop the model was also the data used to validate the model, the results could be meaningless. Since AFOTEC developed its model based only on theory, no data was used in developing the model; therefore, it was ensured that the results would not be biased.

The next step was to fit the data to the model using the nonlinear regression methods. The regression techniques determined a best fit of the data to the model and solved for the two parameters "a" and "b." Eighty percent of the data was used in determining the two parameters. Then using the model, predictions were made and compared with the actual values of the remaining twenty percent of the data.

The validity of the model was analyzed using the output provided by the SAS nonlinear regression program for all six sets of data. In particular, the model was evaluated on the shape of the plotted data, the coefficient of determination (R^2), the confidence intervals placed on the parameter estimates, and the an analysis of the residuals.

The most obvious sign indicating the invalidity of the model was found in the data plots (See Figure 10). The figure below depicts the S-shaped curve that was discovered for all six sets of data.

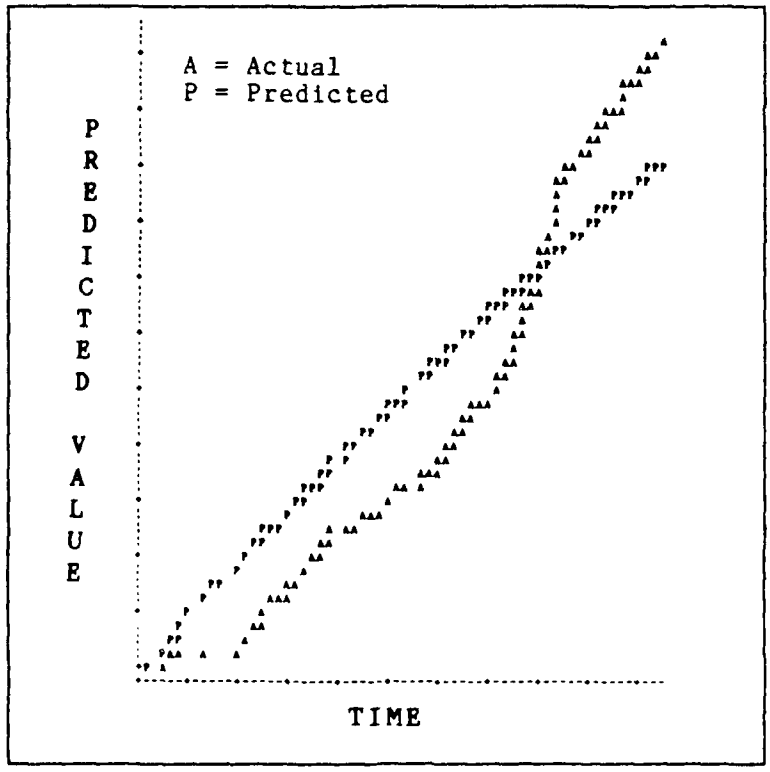


Figure 10: Model Versus Actual for AFOTEC Model

For the model to be valid, the curve would be expected to increase sharply at first and then slowly level off, as depicted in the model curve plotted with the symbol "P." The possible causes of this S-shaped Curve may be due to several reasons, as discussed in Chapter II. (Note: graphs of all sets of data are provided in Appendix E).

The confidence intervals on the "a" and "b" parameters were also an indicator of the model being invalid. The SAS output provided a 95% confidence interval on the estimate of the two parameters, and the results for each data set are shown in Table II.

Table II: Parameter Intervals Analysis for the AFOTEC Model

DATA SET	PARAMETER a LOWER	a UPPER	b LOWER	b UPPER
1	-137.47	2137.47	-0.044	0.352
2	39.02	51.71	12.303	21.909
3	-10296.30	20296.30	-0.244	0.464
4	-3785.74	15785.74	-0.147	0.547
5	119.49	7880.50	-0.007	0.192
6	-2283.09	4283.09	-0.199	0.361

For the model to be valid, it was expected that these intervals should not include the value zero. In four instances, the confidence interval on the parameter "a" included zero; and in all cases but one, the interval on "b" included zero. Only one set of data passed the test for both parameters.

When the confidence interval of the parameter includes both positive and negative values, it implies a possibility of the parameter also being negative. A negative value does not make sense in the case of the "a" parameter, because it is not possible to have a negative number of faults in a software program. Similarly, if "b" were negative, it would suggest that the cumulative number of faults would eventually become negative.

The coefficient of determination (R^2) was the next factor to be evaluated. The R^2 was calculated using the following equation:

$$R^2 = 1 - SSE/SST \quad (14)$$

where

SSE = Sum of Square Residuals
SST = Corrected Total Sum of Squares

Again, the coefficient of determination gives a measure of how closely the data fits the model, with 1.0 being an exact match and 0.0 meaning no correlation between the data and the model. The goal was to have the coefficient of determination to be greater than 0.75 in all cases, and for the average to be greater than 0.85.

The results generated from the AFOTEC data are displayed in Table III. The outcome of the test shows all of the R^2's being greater than 0.75; however, the average is below the 0.85 criteria. Although some of the coefficients of determination were close to the goal, the fact that the shapes

of the curves do not match, as noted above, gives strong evidence that the model may not be valid.

Table III: Coefficient of Determination Analysis for the AFOTEC Model

DATA SET	R SQUARED
1	0.808
2	0.944
3	0.782
4	0.876
5	0.813
6	0.769
AVE:	0.832

The last factor used to judge the validity of the model was the analysis of the error or residuals in the model. For each set of data, the differences between the actual data points and the points predicted by the model were calculated. Then, the mean and the standard deviation of the residuals were calculated.

The criteria for this test was to have the mean of the residuals within $\pm$ 10 faults, and the standard deviation of residuals should be small. The results of the analysis are found in Table IV.

The mean of the residuals meets the established criteria in only three of the six data sets. The large values for the mean residuals suggest there is also large error associated with the model. Observing the standard deviations, it is noted that in all cases, except for data set #2, the standard

deviations are judged to be excessively large. A large standard deviation implies that, in some cases, the model is making large errors. Even if the mean residual was zero, the standard deviation may still be large, because a large positive error could negate an equally large negative error.

Table IV: Residual Analysis for the AFOTEC Model

DATA SET	RESIDUALS MEAN	STD DEV
1	-9.27	42.50
2	-0.53	3.33
3	-41.18	120.26
4	-54.49	120.91
5	-18.41	152.88
6	-5.98	22.59

The next objective was to test the predictive powers of the model. Table V presents the results of this analysis. From the table, it is evident that the mean residual for each set of data is outside or the required $\pm$ 10 fault range. The variance in the residuals is also judged to be excessive in three of the six cases.

Based on the results of the four validity tests and the test on predictions, the AFOTEC Software Reliability Model cannot be proven to be a valid software reliability model. In Chapter V - Conclusions and Recommendations, the significance of these findings will be discussed; and in Appendices A and B, two recommended improvements to the AFOTEC

Model will be presented and tested for validity using the same criteria discussed in this chapter.

Table V: Analysis of Predictions for the AFOTEC Model

DATA SET	RESIDUALS MEAN	STD DEV
1	53.34	6.69
2	1.24	4.41
3	104.75	21.15
4	84.88	43.24
5	230.42	33.95
6	18.72	3.43

Model Assumptions

If the model was judged valid, the next step would have been to determine the assumptions under which the model is valid. Since the model was not found to be valid, only some general observations can be noted about the data, rather than the model.

The first observation deals with the shape of the data. As noted earlier in the chapter, the data for each case exhibited an S-shape. Although the data does not plot as expected by the model; it appears that space, aircraft and communications systems all act in a similar fashion, as indicated by the S-shaped graphs.

The S-shaped data may also lead to an assumption that there are two distinct phases occurring in the testing: a start-up phase, and a steady state phase. The initial flat portion of

data would represent the testing start-up, and the remaining data would describe the full scale or steady state testing. However, this assumption can not be proven by the results of this research.

It was also observed that the effect of using calendar dates as the independent variable did not change from one set of data to the next. It could be assumed, therefore, that during the testing phase, the use of calendar dates is a valid method of measuring time between software failures. Again, this assumption should receive further testing to ensure its validity, because, it is also possible that if actual test time were used rather than calendar time, the data may not have taken on the S-shape.

Summary and Conclusions

As discussed in this chapter, the AFOTEC Software Reliability Estimation Model cannot be considered to be valid using the given data. The model did not pass any of the test required for validity; however, in Appendices A and B, the model is again checked for validity, but under different assumptions.

Appendix A considers a variation of the AFOTEC Model with the exclusion of the initial portion of data collected prior to reaching a steady state testing capacity (Model A). By omitting the initial data, the model assumes that the system being tested must already be in the steady state phase. The

results found in Appendix A prove the AFOTEC Model may be valid under this assumption.

Appendix B considers a piece-wise model (Model B) that follows the S-shaped pattern of the data. This model could be useful in demonstrating when a program has advanced past the initial stages of testing and into a steady state. The results found in Appendix B verify the validity of the piece-wise model.

V. Conclusions and Recommendations

Introduction

The purpose of this research was to judge the validity of the AFOTEC Software Reliability Estimation Model. A statistically based methodology was used to determine how closely the results predicted by the model corresponded with the actual sample data. The conclusion drawn from the analysis performed in Chapter IV suggests that the AFOTEC Model is not valid.

This chapter will discuss possible causes of the for the invalid finding in Chapter IV and will recommend several changes that could be made to the model to improve its applicability and validity.

Conclusions

The general conclusion of this research is that the AFOTEC Software Reliability Estimation Model is not valid based on the data used in the validation tests. However, as demonstrated in Appendices A and B, the model can be considered to be valid if the initial portion of data is handled in a different manner.

After seeing the initial results of the validity tests, Captain Mike McPherson of AFOTEC was questioned about the testing procedures used at AFOTEC and what reasons might lead to the data exhibiting the S-shape. Captain McPherson stated two facts that could help to explain the shape of the data.

First, the testing of a system can sometimes be delayed due to a major program or one with a higher priority. For example, when the B-1B Bomber was being tested at AFOTEC, it had a higher priority for the use of the range and testing facilities than the other systems being tested at that time; therefore, these other systems were not being tested at the full capacity (28). When a higher priority system takes test time from another system, the result is to have fewer faults found than would have been expected; thus, the plot of the data would tend to be flatter.

Second, when the testing of a system begins, an initial start-up period is common (28). The start-up period is the time between the start of the testing and when the tests are being performed at 100% capacity. Testing frequently begins before all required equipment, personnel and parts are available. The main reason for starting the tests prior to being fully prepared is to minimize any possible schedule slips. When a system being tested exhibits a start-up phase, again, the result is to have fewer faults found initially than would have been expected if the system was tested at full capacity. Thus, the result of starting tests early is to have a flat portion in the data at the beginning of the testing.

Since the shape of the data can be explained, new or revised models can be developed. The models discussed in Appendices A and B are two such models. From the outcome of the validity test conducted on these two models, it has been

concluded that these two models may be valid for estimating software reliability.

Model A operates under the assumption that software testing must reach a steady state before the model can be used. Hence, the initial portion of data is discarded, and the model is uses only the latter portion of data, where a sharp increase in the number of faults detected is observed.

The results discussed in Appendix A provide evidence that Model A is a valid method of predicting software reliability. Only one data set run in Model A failed a validity test; all others passed.

Model B is similar to Model A, except it attempts to model both portions of data. The first portion is emulated with an exponentially increasing model, and the second portion uses a version of the AFOTEC Model.

In Model B, the first model estimates when the testing will reach a steady state, and the steady state point is then used in the second model to estimate reliability. Appendix B discusses the results of the validity tests performed on Model B. The conclusion drawn from these results is that Model B is also a valid method of estimating software reliability.

Recommendations

Recommendations resulting from this research fall into two categories. The first category deals with recommended improvements to the AFOTEC Model and suggested applications

of the AFOTEC Software Reliability Estimation Model. The second category deals with suggested areas of further research.

Improvements and Application. The results of this research fail to prove the AFOTEC Model to be valid; however, Appendices A and B represent two possible improvements that can be made to the model for it to achieve validity. Based on the ease of use as described above, Model A is recommended for use by AFOTEC for predicting software reliability, because it follows the same logic and format as the basic AFOTEC Model; therefore, the AFOTEC personnel should be familiar with its operation and assumptions. Although Model B also has a similar logic in its latter portion, it requires more time and effort in its operation.

Model A should be easier to tailor for specific applications. If a testing program has a low priority or exhibits a start-up phase, the initial data may be discarded to use the model. Note, however, in the case where no start-up phase occurs, Model A is equivalent to the AFOTEC Software Reliability Model.

Although Model B may more accurately represent reality, Model A is still recommended due to its ease of use. Since the Air Force is regularly subjected to transient personnel possessing a wide variety of backgrounds and experience, it is important to have tools that are easy to learn, teach and operate.

Future Research. The research conducted in this thesis just begins to expose the "iceberg" of software reliability. As mentioned in Chapter I, it is important to all people who buy, develop, or use software systems that they have reliable systems. In general, any area of research dealing with the topic of software reliability is an important topic that warrants further study. However, dealing specifically with the topics discussed in this thesis, there are several areas recommended for further study.

First, it is important to develop models for estimating the reliability of software during life cycle phases other than the testing phase. Models should be designed for both earlier and later phases in the software life cycle. One particular area of research could study the AFOTEC Model to determine if it is valid during other phases of the life cycle.

Another related topic could be to compare various methods and models to determine which are more accurate or better suited for use in the Air Force, and during which phases they are best suited.

A second area is in the development of other improvements to the AFOTEC Model. Rather than discarding data or having a piecemeal model, it would be beneficial to have one model that handles all cases. By having one model, it would not require the operator to make subjective decisions about which model to use nor would he/she be required to guess which data should be thrown away. If one model managed both the case of

data with and without a start-up phase, the operator could do his/her job quicker and easier. It is also recommended that the AFOTEC Model be retested using actual test time data rather than calendar time.

Third, methods for combining software and hardware reliabilities into a system reliability should be developed and validated. For a military service, the goal is to be prepared for the event of a war and to protect the public. By having reliable systems, the services would have more systems available to protect the public, and these systems would be operating longer. If we have a valid method of assessing system reliability, the Air Force and other services would be better and more accurately able to determine this availability.

Summary

The purpose of this research was to determine the validity of the AFOTEC Software Reliability Estimation Model. Although the model was not found to be valid, the theory and logic of the model is believed to be valid, and several improvements have been recommended for the model and have been validated.

It is important for all Americans to realize the significance of software and system reliability in our future. In this age of rapid growth of software intensive systems, software will have a critical effect on system reliability. We must continue to explore the topics of software and system reliability if we intend to survive in the future.

Appendix A: Analysis of Model A

Introduction

This appendix contains the results of the analysis of a proposed improvement to the AFOTEC Software Reliability Model. The methodology and tests are the same as described in the previous chapters.

Description

Model A operates under the assumption that software testing must be at a steady state before the model can be used. Hence, the initial portion of the data is discarded, and the model uses only the latter portion of data, where a sharp increase in the number of faults detected is observed.

To use Model A, the initial data is discarded until testing reaches a full capacity or until a sharp increase in the number of faults detected is observed. Now, the model can be used just as the AFOTEC Model. The dates are converted into chronological numbers as the independent variable, and the cumulative number of faults detected from this point on is used as the dependent variable.

Next, regressing Equation (9) with the new data, the "a" and "b" parameters are estimated. Once these parameters have been determined, they are entered into Equation (10). This calculation provides an estimate of the mean time between failures for the software.

Results

The first sign of Model A being an improvement over the AFOTEC Model was found in the graph of the data. Figure 11 presents a graphical view of the data and the models predictions. Note, Appendix E contains graphs of all data sets. It is clear that Model A fits the data closer than the AFOTEC Model, as compared with Figure 10.

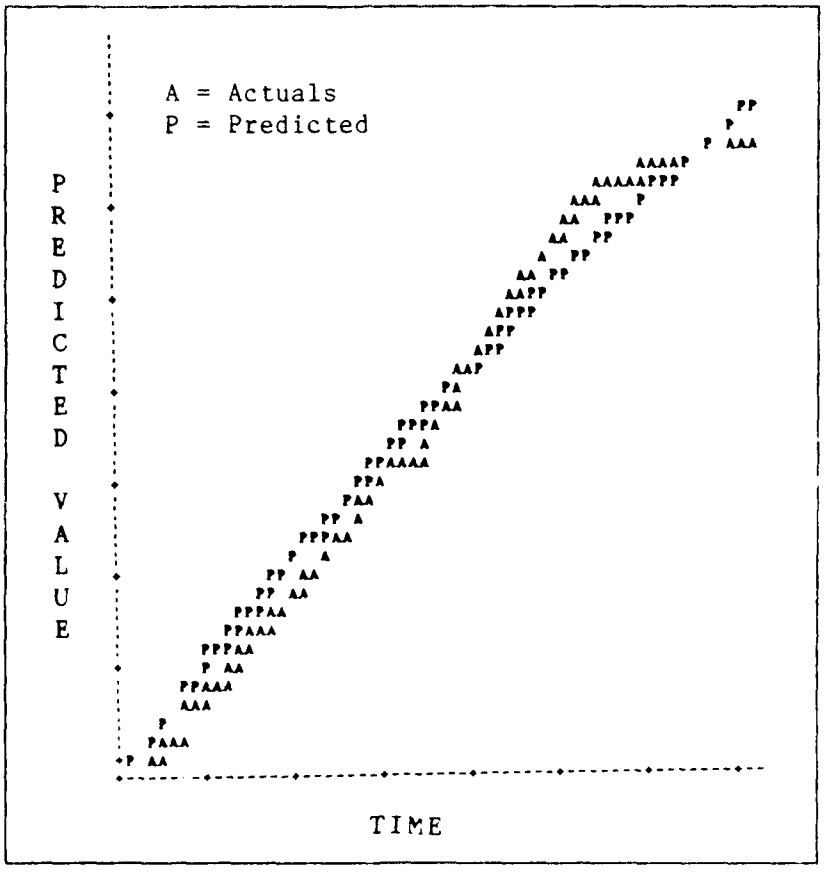


Figure 11: Model Versus Actual for Model A

Next, the confidence intervals on the model parameters were ana'yzed. The outcome of the analysis is provided in Table

VI. The results show that each set of data, except set #6, passed the test for both parameters.

Table VI: Parameter Interval Analysis for Model A

DATA SET	PARAMETER a LOWER	a UPPER	b LOWER	b UPPER
1	176.37	1823.32	0.013	0.379
2	39.02	51.71	12.303	21.909
3	1475.76	2524.23	0.421	0.794
4	1858.66	10140.33	0.079	0.520
5	710.26	7289.73	0.024	0.375
6	-2445.73	4445.73	-0.355	0.627

The outcome of the coefficient of determination analysis, displayed in Table VII, show each R^2 being greater than 0.75 and the average greater than 0.85. These statistics show an improvement over those of the AFOTEC Model, and indicate the data to have a higher correlation with Model A.

Table VII: Coefficient of Determination Analysis for Model A

DATA SET	R SQUARED
1	0.884
2	0.944
3	0.973
4	0.984
5	0.956
6	0.766
AVE:	0.918

The residual data from Model A was then evaluated. An improvement in the mean residuals, as compared to the AFOTEC

Model, was found to be as much as 90 percent lower in one case. The results of the analysis are exhibited in Table VIII.

Table VIII: Residual Analysis for Model A

DATA SET	RESIDUALS MEAN	STD DEV
1	-6.82	31.49
2	-0.52	3.33
3	-8.30	34.43
4	-1.19	35.58
5	-6.09	38.12
6	3.87	14.62

The outcome of the analysis shows each set of data having a mean residual less than $\pm$ 10 faults, and shows a substantial improvement in the standard deviations. In the case of data set #5, the improvement resulted in a standard deviation approximately three times lower than in the APOTEC Model.

The last test was to evaluate the predictive error in the model. Again, improvements were noted. The data presented in Table IX, shows only data set #1 failing to meet the criteria, and the deviations to be slightly better than those of the APOTEC Model.

Based on the results of the analysis discussed above, it was judged that Model A is a definite improvement over the APOTEC Model, and that although a few data sets failed test, Model A appears to be valid.

Table IX: Analysis of Predictions for Model A

DATA SET	RESIDUALS MEAN	STD DEV
1	36.36	4.22
2	1.24	4.41
3	-2.23	39.68
4	5.25	18.91
5	-6.89	4.32
6	-5.87	5.67

Appendix B: Analysis of Model B

Introduction

This appendix considers a piece-wise model (Model B) that follows the S-shaped pattern of the data. This model could be useful in demonstrating when a program has advanced past the initial stages of testing and into a steady state. The results found in this appendix verify the validity of the piece-wise model.

Description

Model B is used by dividing the data into two sets. The first set of data is regressed against the equation:

$$Y = \exp(c * t) \qquad (15)$$

where

Y = cumulative number of faults
c = a constant representing the fault detection rate
t = time in consecutive days

This first part of the model helps predict when testing will reach full capacity. The testing is assumed to reach full capacity at the time, t_0, when the graph begins to climb rapidly.

After the testing has reached a steady state, the following equation is used to model the discovery of software faults:

$$Y = \exp(c * t_0) + a'\{1-\exp[-b(t-t_0)]\} \qquad (16)$$

where

Y = cumulative number of faults
c = a constant representing the fault detection rate
t_0 = the at which the model switches from the start-up phase to the full scale testing phase

$a' = a - \exp(c * t_0)$
b = the fault detection rate for full scale testing
t = time in consecutive days

Before using this second portion of the model, the time to reach full scale testing (t_0) must be determined from Equation (15). Now, a nonlinear regression of Equation (16) is performed to determine the values of a' and b. Finally, an estimate of the total number of faults can be calculated using:

$$a = a' + \exp(c * t_0) \qquad (17)$$

and the mean time between fault estimated by Equation (10). The independent and dependent variables for this model are determined similarly to that in Model A.

It should be noted that Equation (16) is the same as the equation used in Model A, except the model is shifted up by the amount of faults detected during the start-up phase, and shifted right by the amount of time elapsed during the start-up phase. This shifting was not present in Model A, because the initial portion of data was discarded.

Results

The results of the validity analysis performed on Model B are approximately the same as the results for Model A. presented in Appendix A. The similarity in results is due to the similarities in the two models and the shifting discussed above. The two models are exactly the same except for this shifting that occurs in Model B. For example, if a set of

data did not have a start-up phase, Equation (16) would simplify to be equivalent to Equation (9). Model B, therefore, is also judged to be a valid method of estimating the reliability of software.

Appendix C: AFOTEC Paper

Predicting System Reliability: Software and Hardware

Mr. J. Wiltse
Capt M. McPherson
Capt K. Holmquist

Abstract - This paper presents a practical method of combining software maturity data with hardware failure data to predict system reliability. Currently, the Air Force Operational Test and Evaluation Center (AFOTEC) considers software to be 100 percent reliable for system reliability projections and therefore, these projections are based solely on hardware failure data. We propose coupling the results of a hardware model with the results from a decreasing software failure rate model with imperfect debugging. Software maturity data gathered during developmental and operational testing is used as input to the software failure rate model. The effects from software enhancements developed during the block release cycles and fault introduction through error correction are added to give a comprehensive yet practical measure of software reliability. These factors give the software model a predictive capability that some models lack. An estimate of the total number of faults in a software system is determined from the failure rate and a software mean time between critical failure (MTBCF) is defined.

A review of classic hardware reliability modeling used during the development and operational test phase is presented first. Hardware reliability is discussed including previous treatment of software failure data. This is followed by a description of methods used to demonstrate and project software reliability. Finally, a discussion on combining hardware and software reliability model results to derive a system reliability number is presented. An example reinforces the ideas presented.

Predicting System Reliability: Software and Hardware

by
J. D. Wiltse
M. McPherson
K. Holmquist

1. INTRODUCTION

System reliability can be defined in terms of mean time between critical failure (MTBCF). In specifying a system reliability requirement, the user states his needs for a mature system. Since the system does not mature for years after operational test, the mature system reliability required by the user is predicted from the operational test data. More systems are becoming software intensive; therefore, the software effects on the overall system reliability must be considered. The reliability of the software in Department of Defense (DOD) systems is demonstrated during operational testing but seldom predicted.

During developmental and operational tests the systems are normally not mature and the reliability requirements stated are for a mature system. Therefore the reliability demonstrated during test is used to project the mature reliability. During each test, all failure data is collected. This data is then analyzed and each failure is categorized as either critical or non-critical. We then calculate the mean time between critical failure for the system using all the critical failures observed during the test. The critical failures can include both software and hardware failures. A demonstrated MTBCF is reported based on these failures.

To project the reliability to maturity, defined as initial operational capability (IOC) plus two years, the testers use a reliability growth program

specified and funded by the system program office. The reliability growth plan used varies from program to program. Many use the Duane Growth Model, others use the Army Materiel Systems Analysis Activity (AMSAA) Model, or engineering analyses. Whichever model is specified, the data is analyzed to determine if the model fits the data. In projecting to maturity, all software faults are considered fixed. So the projected MTBCF includes only hardware failures. In reporting the projected MTBCF, the testers report the point estimate, as well as the confidence limits, for the reliability, if possible.

Current test and evaluation methodologies assume all software faults will be fixed by system maturity. System reliability is therefore projected solely on the basis of hardware failures. An erroneous picture of system reliability is presented to the user and senior decision makers as shown in Figure 1. System reliability is typically presented as a demonstrated system MTBCF which includes both hardware and software. For predicting future system reliability, the software is assumed to be perfect (as shown by the step function Delta 1) and hardware reliability is then grown to a mature value. This leads to a misconception that the grown hardware reliability is the system reliability. If software is properly accounted for in total system reliability, the mature system MTBCF will be lower (Figure 2) by Delta 2. The effect that software has on system reliability has been long overlooked and must be addressed since top level decision makers are now asking if the system reliability projection includes the software's contribution.

Presently, there are many methods for predicting software reliability, most of which fit into the following categories: Time between failure models, failure count models, fault seeding models, and input domain models. In developing a model to be used at AFOTEC, practical features from existing

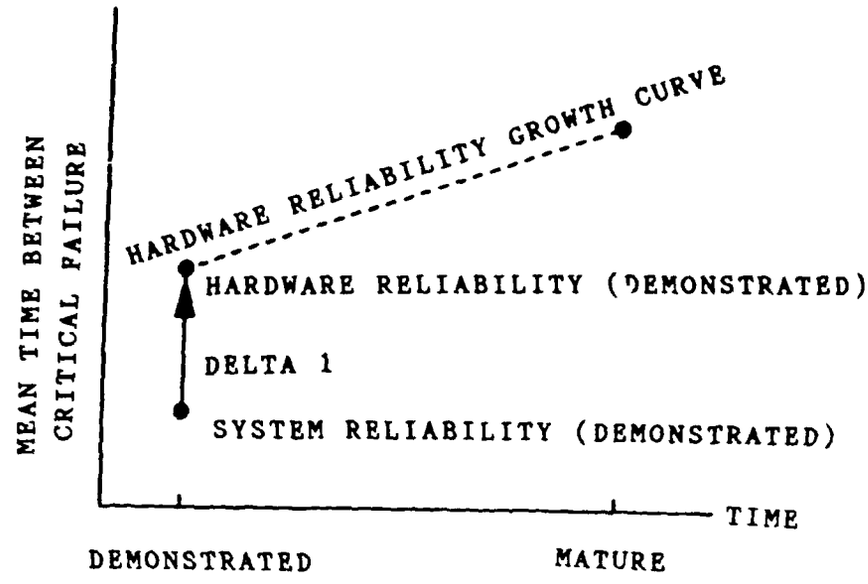


Figure 1

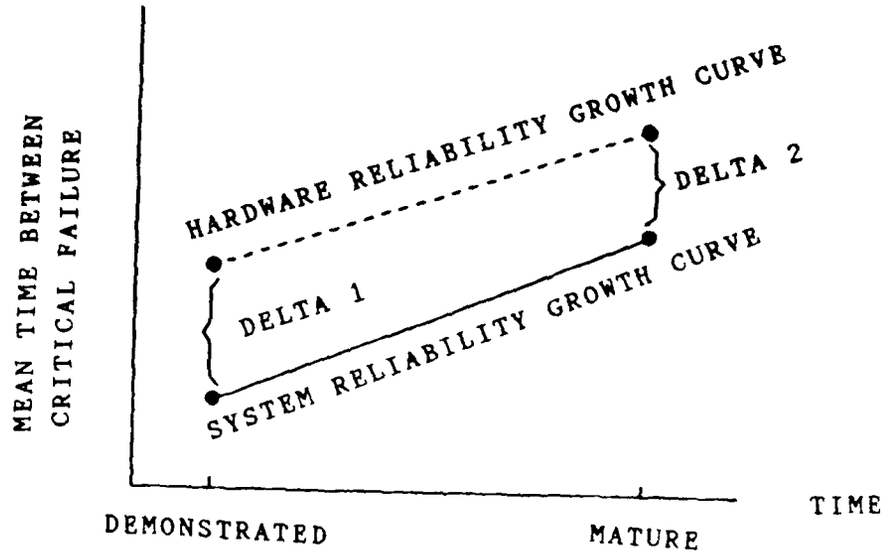


Figure 2

models were combined with our maturity method as well as other constraints.

A BRIEF DESCRIPTION OF SOFTWARE MATURITY

Software maturity is a measure of the software's progress in its evolution toward meeting user requirements. Several development indicators give insight about this progress. The rate at which software errors are being discovered and fixed is the primary indicator of software maturity.

Software changes are made to correct errors in the software design and programming. Errors result in deficiencies which we will call faults. Each fault has a unique impact in the system and is categorized by one of five different DOD standard severity levels with associated weights (Figure 3). Severity levels range from minor inconveniences to major problems that can cause system abort. The faults (or changes) are multiplied by their respective severity weight to produce values called "change points". The accumulated change points are tracked over time. Two curves: Originated and Closed are plotted which illustrate software maturity (Figure 4).

The Originated curve is determined by accumulating the first occurrence of each change point plotted versus time. The greatest software change rate occurs early during software testing. As problems are worked out of the software, this change rate decreases to some steady-state value. The slope of the curve decreases with time because the rate of discovering errors, and the severity of those errors, decreases with time.

In addition to plotting software changes over time, we plot a second curve (called the "Closed" curve) based on software changes implemented or fixed. This gives an indication of the rate at which software faults are corrected compared to the rate at which they are being discovered. The faults that have

Severity Level	Severity	Description	Severity Weight (Points)
1	System Abort.	A software of firmware problem that results in a system abort.	30
2	System Degraded. No Work-around.	A software of firmware problem that severely degrades the system and no alternative work-around exists (program restarts not acceptable).	15
3	System Degraded. Work-around.	A software of firmware problem that severely degrades the system and there exists an alternative work-around (i.e. system rerouting through operator switchology; no program restarts).	5
4	Software Problem. System not Degraded.	An indicated software of firmware problem that does not severely degrade the system or any essential system function.	2
5	Minor Fault.	All other minor deficiencies of non-functional faults.	1

Figure 3

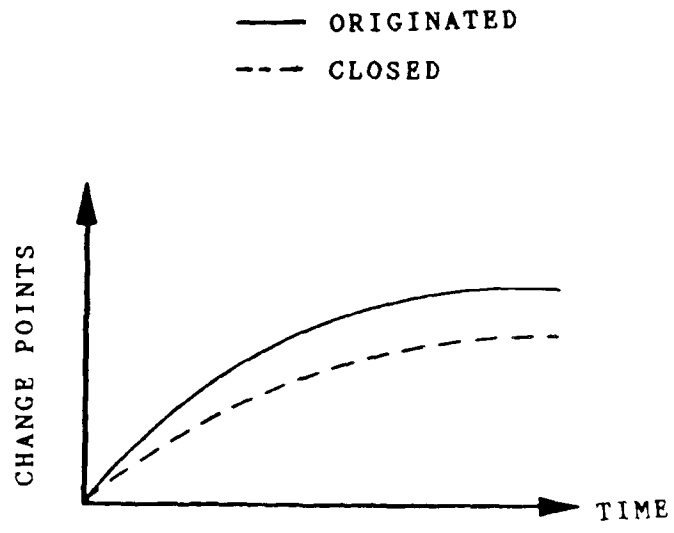


Figure 4

been corrected are weighted using the same severity scale as the faults that have been discovered. As the software matures, the gap between the Originated and Closed curves should narrow (this concept is referred to as "closure").

The minimum data required for the software maturity metric consists of the following:

1) Software problem number - a unique identifier used to distinguish one software problem from another.
2) Affected software configuration item - the particular program where the software problem was discovered.
3) Severity of the problem - a numeric value (1 thru 5) of the impact the software problem has on the system.
4) Date of initial discovery - the date the software problem was identified.
5) Date problem was fixed - the date the software problem was closed.
6) Description of problem - short narrative describing the software problem (needed for traceability between software problems).

To use software maturity data for software reliability, we use only severity level 1 and 2 software faults without the weighting factor.

2. MODEL DEVELOPMENT

A model is required to determine the effect of software critical failures on system reliability assessments. The fact that AFOTEC is an operational test organization insists that we choose a method that uses actual operational test data to make a software reliability prediction. Also, we need to choose a

method that allows us to relate failure data to calendar time which is a constraining factor of some models. Also, this methodology must use system level observables and existing failure reporting systems. Critical failure data are to be taken from the software maturity data collected during testing. Historical software maturity data has exhibited an exponentially decreasing failure rate process. Reliability assessments for systems containing both hardware and software must be based upon compatible mathematical foundations and a consistent set of terms which suggests that the chosen must be of an exponential nature. We emphasize the selection and development of a software reliability assessment model which is most compatible with hardware reliability theory and practice.

BASIC MODEL

An exponentially decreasing failure rate process is central to the model we have chosen. Based on the above considerations, a description of the software failure rate process as proposed by Goel and Okumoto was selected as the core of our model which has the following form:

$$m(t) = a(1 - e^{bt}) \qquad (1)$$

where $m(t)$ is the expected accumulated number of critical software faults at any time t, a is the total number of critical software faults (a constant) in the system to be observed eventually, and b is the fault detection rate per fault (also a constant). Musa has demonstrated the validity of using calendar time in software reliability modeling. We have observed this same failure rate process across calendar time in APOTEC's software maturity data.

This basic model assumes that each fault causes only one failure and is corrected before causing a second failure. Without further modification, this model also assumes that each fault is fixed perfectly (i.e. no new faults are introduced as a result of fixing a fault) and that there are no faults introduced whenever an enhancement is made. Modification to the basic model which address imperfect debugging and errors introduced from enhancements will be presented.

To use this model in a predictive mode, we curve fit software maturity test data to equation (1) and obtain the constants a and b. This equation is then differentiated to obtain the new fault discovery rate to give the following:

$$dm(t)/dt = abe^{-bt} \qquad (2)$$

Next the time (t_m) at system maturity is used in the above equation to obtain the new fault discovery rate at system maturity which is the reciprocal of the MTBCF for software. This MTBCF can be combined with the hardware MTBCF for an initial combined system MTBCF (figure 5).

In order to calculate an overall system MTBCF, we first project the hardware MTBCF to maturity using whichever model has been specified for the system, and project the software MTBCF using the method described earlier. The next step is to pick an arbitrary time period, t, and determine the number of failures that should occur during the period. To do this use the following equations:

Number of hardware failures in time period t = $t/MTBCF_{HW}$

Number of software failures in time period t = $t/MTBCF_{SW}$

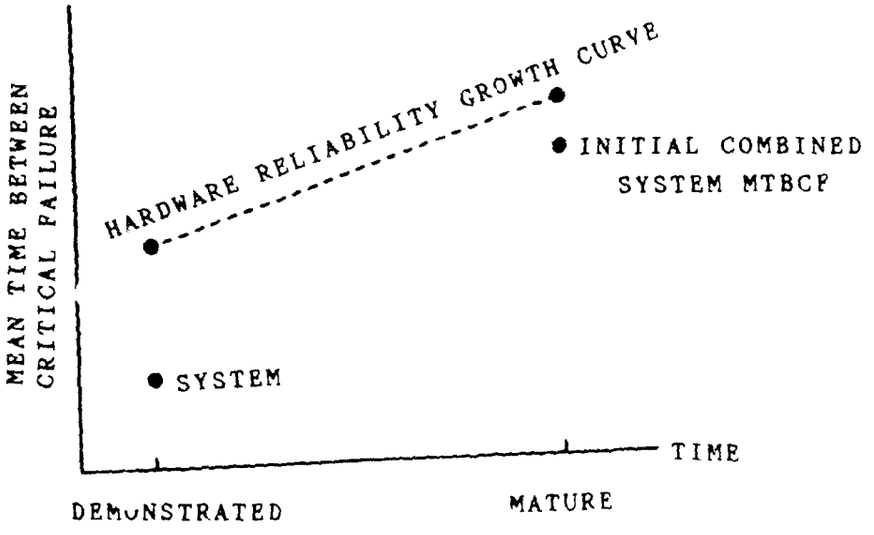

MEAN TIME BETWEEN CRITICAL FAILURE
HARDWARE RELIABILITY GROWTH CURVE
INITIAL COMBINED SYSTEM MTBCF
SYSTEM
TIME
DEMONSTRATED
MATURE

Figure 5

These are combined to give the total number of failures occurring in time period t.

Total number of failures = $t/MTBCF_{HW} + t/MTBCF_{SW}$

To get the combined system MTBCF, divide the total number of failures into the time t.

$$MTBCF_{SYS} = \frac{t}{\frac{t}{MTBCF_{HW}} + \frac{t}{MTBCF_{SW}}} = \frac{1}{\frac{1}{MTBCF_{HW}} + \frac{1}{MTBCF_{SW}}}$$

The $MTBCF_{SYS}$ is the projected system mean time between critical failure.

IMPERFECT DEBUGGING

To increase the predictive accuracy of this model, we need to eliminate as many constraining assumptions as possible. The assumption that when fixed a fault is fixed correctly and no new faults are introduced as a result of fixing a software fault may be removed if we introduce a consideration for imperfect debugging. The latter of these two is more closely akin to the introduction of new faults when enhancements are made and will be treated in that paragraph. The consideration for imperfect debugging describes the effect on software reliability when a fault is not fixed correctly. In an application of Musa's method for addressing imperfect debugging the average of the fault correction/fault detection ratio collected over the life of the test gives an error reduction factor (B). Musa states "it appears likely that B may not vary from project to project" and gives 0.96 as a value. Errors not correctly fixed are treated as additional errors and therefore an increase in the

constant a is necessary. This is done by dividing the constant a by B in equations (1) and (2) to obtain the constant a' which changes these equations to the following:

$$m'(t) = a'(1 - e^{-bt}) \quad (3)$$

and

$$dm'(t)/dt = a'be^{-bt} \quad (4)$$

where

$$a' = a/B$$

This will give a smaller MTBCF for software and thus for the system.

ENHANCEMENTS

The assumption that no new faults are introduced as a result of changing or enhancing the software may be removed by adding a factor to account for software enhancements as suggested by Hecht. The initial fault content of the enhanced code is proportional to the fault content of the original code. This means a straight multiplicative factor may be used in determining the final fault count (the constant a'').

$$m''(t) = a''(1 - e^{-bt}) \quad (6)$$

and

$$dm''(t)/dt = a''be^{-bt} \quad (7)$$

The basic model combined with imperfect debugging and enhancements will give a final software MTBCF. THis final software MTBCF can be combined with the hardware MTBCF for a final combined system MTBCF (Figure 6a).

3. DISCUSSION

What makes this approach different from previous software reliability models and methods is the way it is applied and presented to decision makers. Instead of giving a single reliability number, a confidence interval for system reliability (including software) is presented. Since the most conservative estimate of software reliability is derived from the basic model, the value produced is combined with the hardware reliability to give the upper limit of the confidence interval. The lower bound of the confidence interval is derived by combining the value produced by the complete model (including the imperfect debugging and enhancement effects) with the hardware reliability projection. Figure 6b gives a pictorial representation of system reliability showing the confidence interval provided by including software reliability. Presenting the data in this manner allows the decision maker to consider software in the system reliability projection without being held to a specific number. This estimate of software's contribution to the system reliability projection will be conservative (i.e. because of the limiting assumptions, the system will have more software critical failures than predicted by this model). Although this method does not perfectly present all aspects of software on system reliability, it does address the more significant contributions of software on the system reliability.

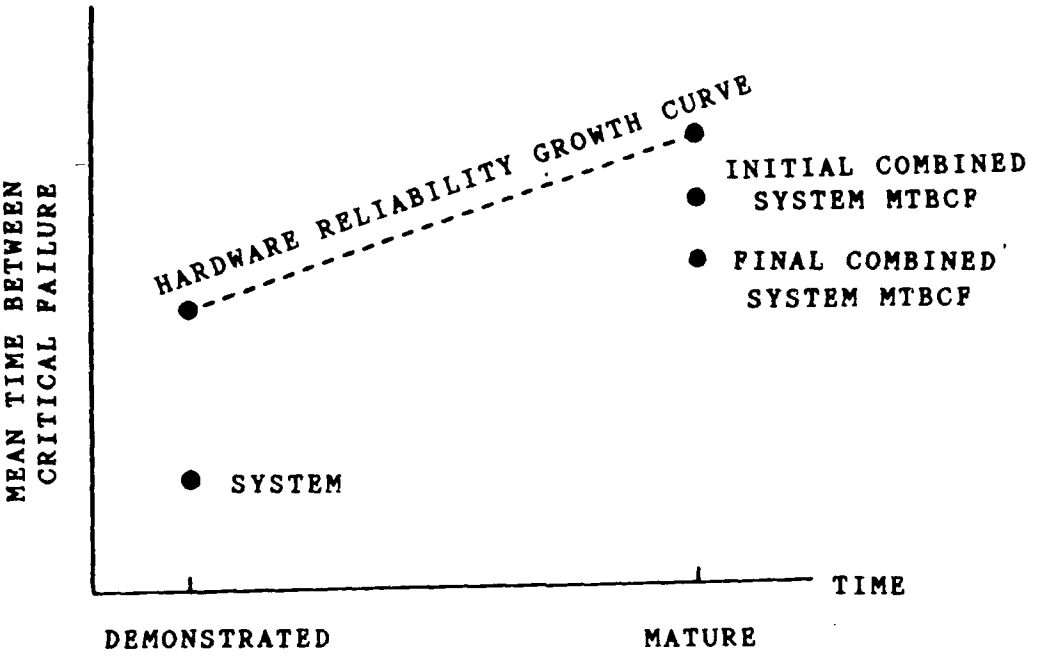


Figure 6a

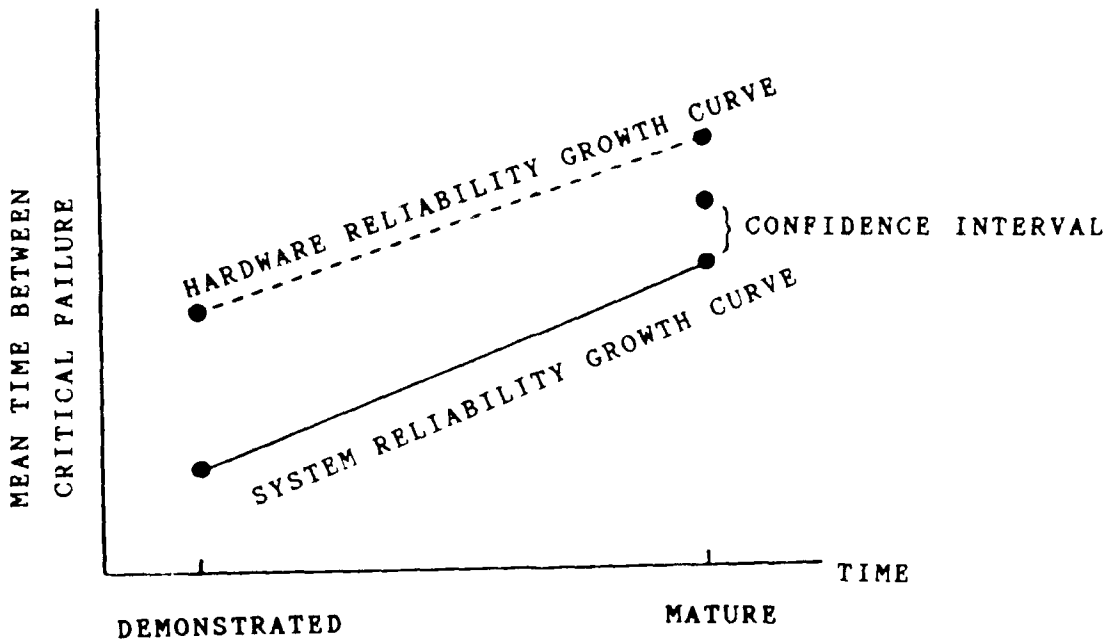


Figure 6b

4. SUMMARY

Software fault data identified throughout testing is used to assess the maturity of system software. Software maturity trend data, which is readily collectable during test, can also be used for software reliability modeling. A basic decreasing failure rate model coupled with compensation mechanisms for imperfect debugging and future enhancements is useful for presenting software's contribution to system reliability. A confidence interval which shows the range of software's effect on system reliability is an acceptable way of introducing software into the system reliability projection.

Appendix D: List of Acronyms and Symbols

AFIT	Air Force Institute of Technology
AFOTEC	Air Force Operational Test and Evaluation Center
AFR	Air Force Regulation
AFSC	Air Force Systems Command
AJPO	Ada Joint Program Office
ASD	Aeronautical Systems Division
a	Total expected number of software faults
a'	a/B
b	Fault detection rate per fault
B	Musa's constant, 0.96
CPCI	Computer Program Configuration Item
CPU	Computer Processing Unit
DOD	Department of Defense
DTIC	Defense Technical Information Center
ENIAC	Electronic Numerical Integrator and Calculator
E	Average instruction execution rate
E_0	Initial number of errors in the program
f	E/I
HOL	Higher order language
h(t)	Failure rate
I	Total number of machine language instructions
INFOCEN	Information Center
K	Constant of proportionality
MSE	Mean square error
MTBF	Mean time between failures
$MTBF_{SYS}$	MTBF of the system
$MTBF_{HW}$	MTBF of the hardware
$MTBF_{SW}$	MTBF of the software

$M(t)$	Cumulative number of failures
$M'(t)$	Fault discovery rate
N	Initial number of errors
n	Total number of faults corrected by time, t
NASA	National Aeronautics and Space Administration
OT&E	Operational Test and Evaluation
PROC NLIN	Nonlinear regression procedure
R&M	Reliability and Maintainability
RADC	Rome Air Development Center
$R(t)$	Reliability
R^2	Coefficient of Determination
SAS	Statistical Analysis System
SEI	Software Engineering Institute
SSE	Sum of square errors
SST	Total sum of square
STARS	Software Technology for Adaptable Reliable Systems
s_e	Standard deviation of residuals
t	Cumulative time on test
x_i	Debugging time between the (i-1)st and ith error

Appendix E: Graphs and Data Plots

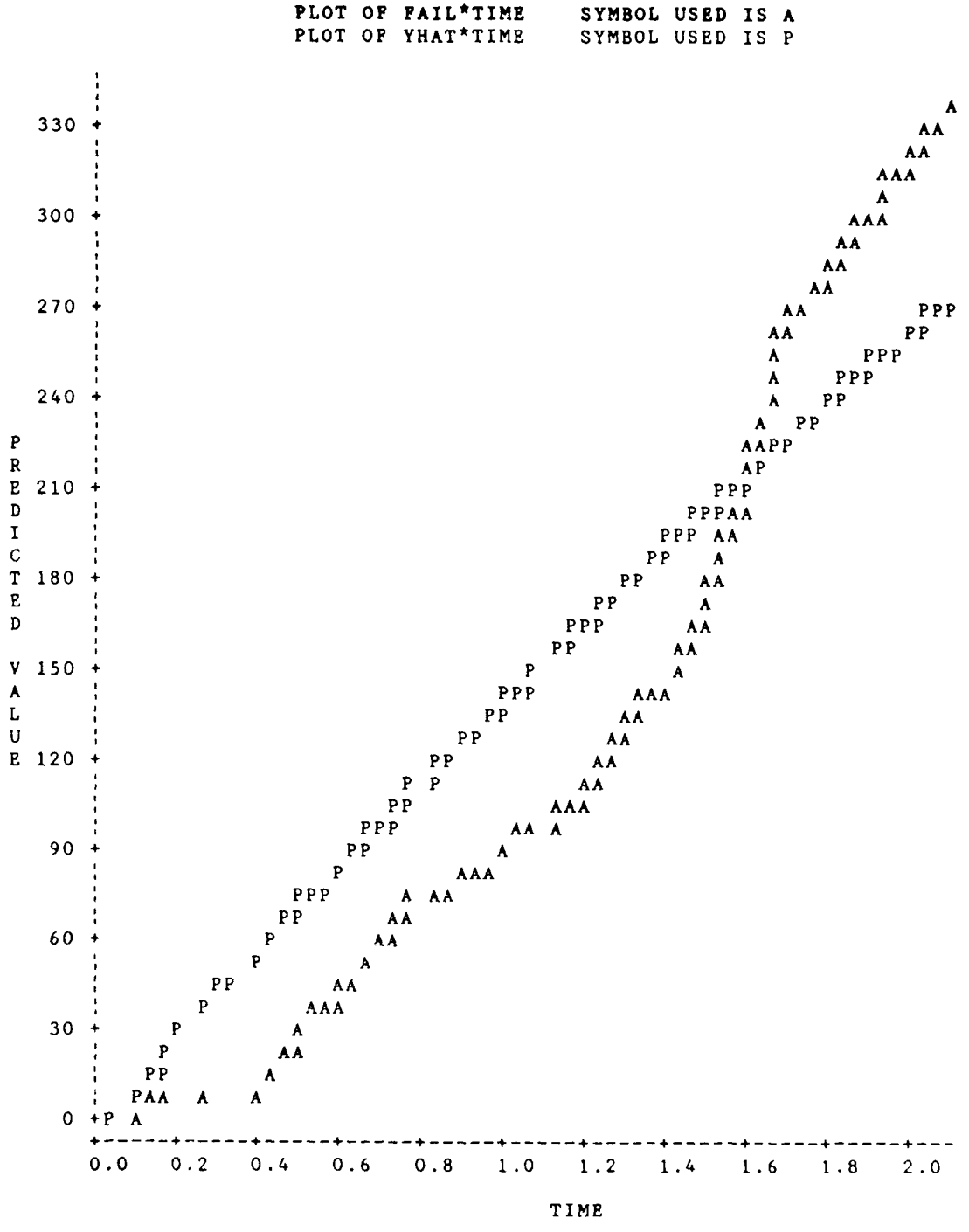


Figure 12: Model versus Actual for AFOTEC Model (Data Set #1)

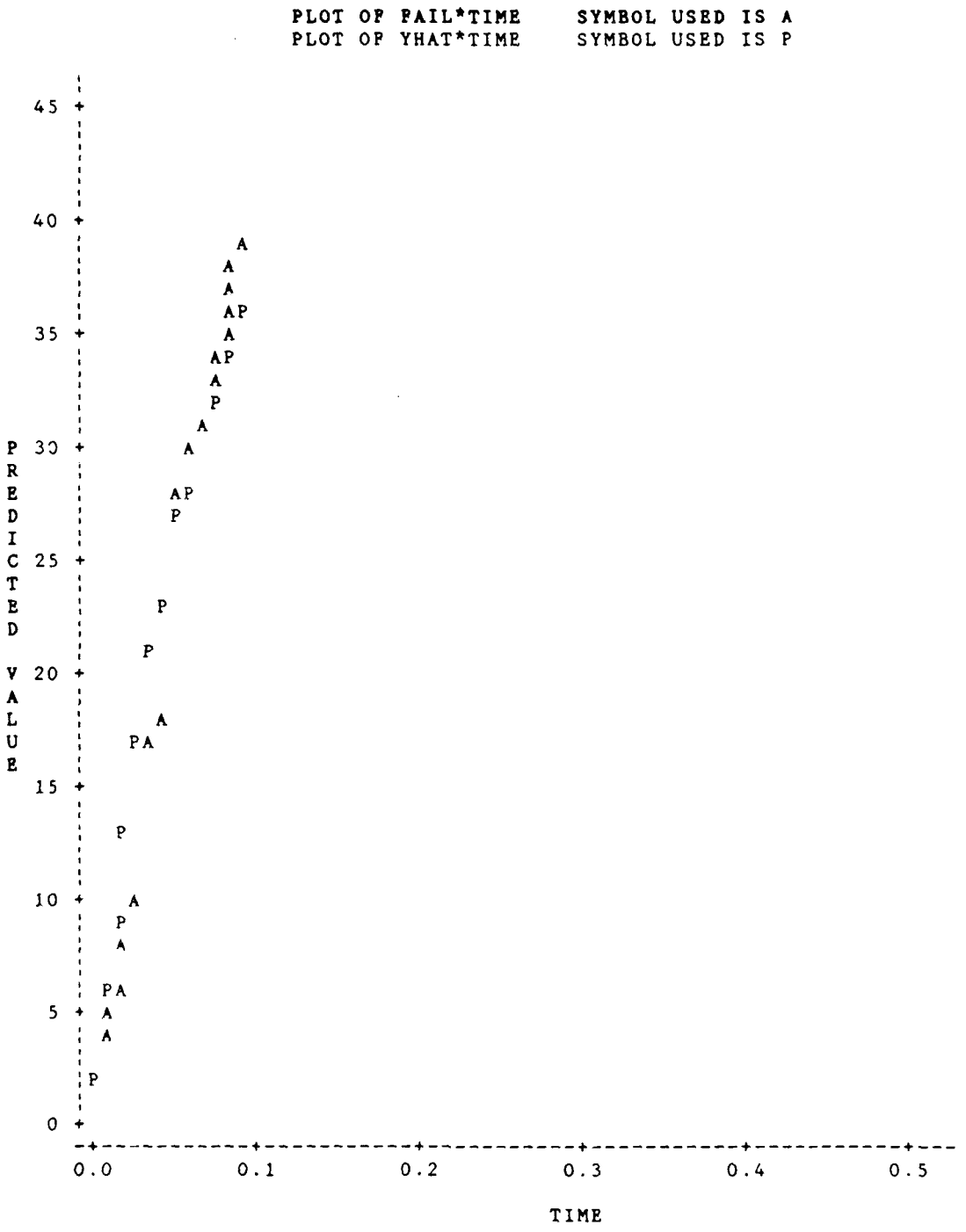


Figure 13: Model versus Actual for APOTEC Model (Data Set #2)

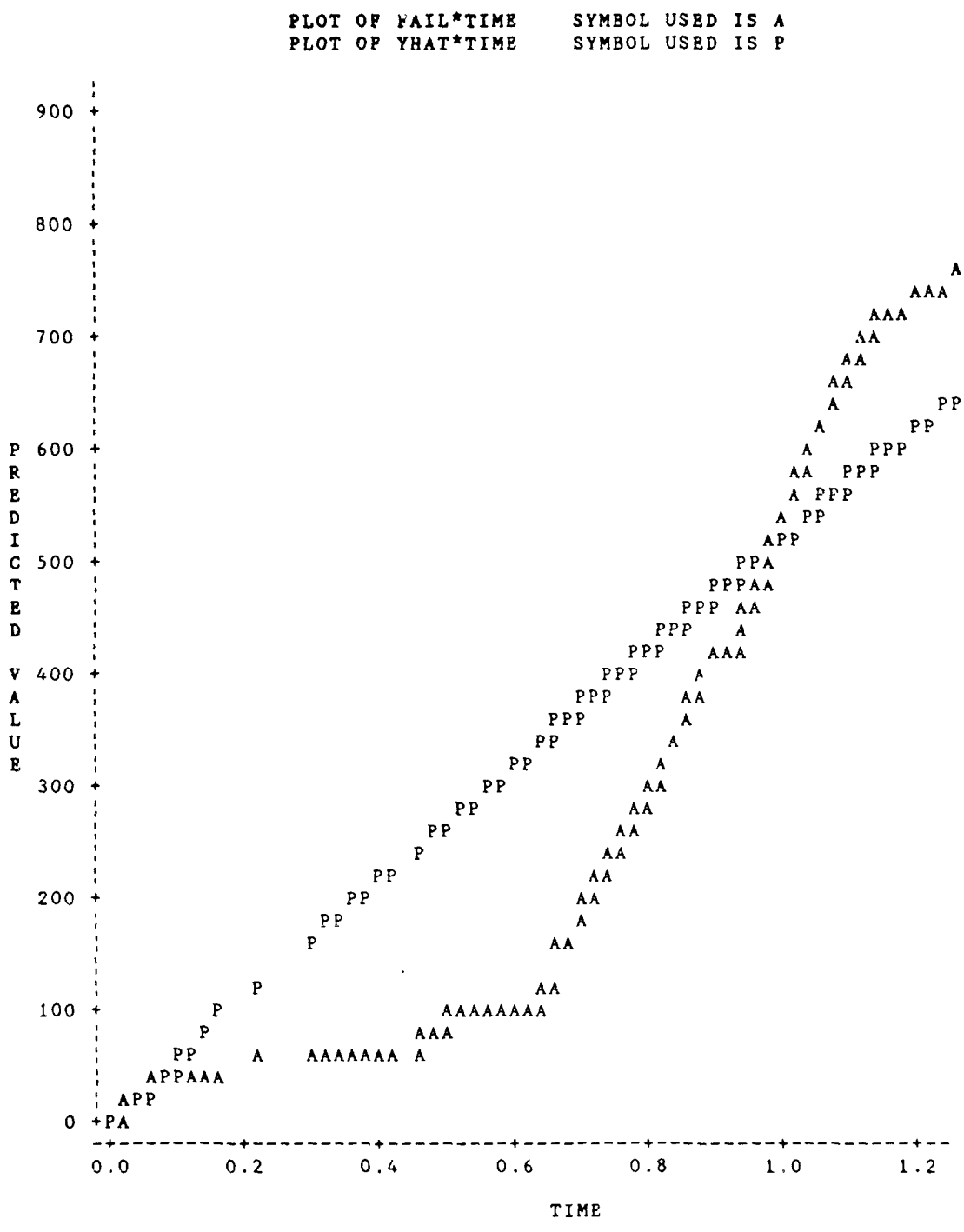


Figure 14: Model versus Actual for AFOTEC Model (Data Set #3)

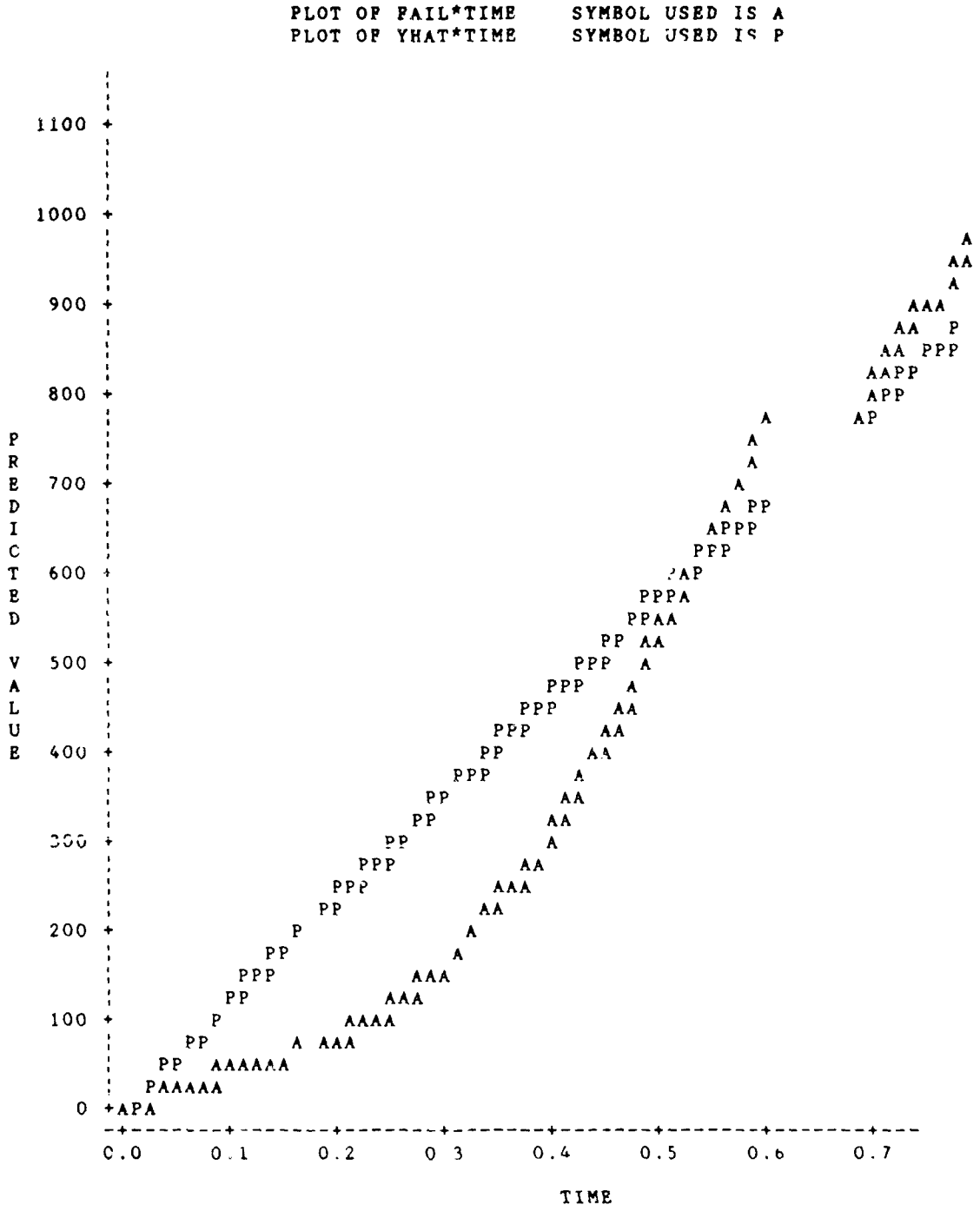


Figure 15: Model versus Actual for AFOTEC Model (Data Set #4)

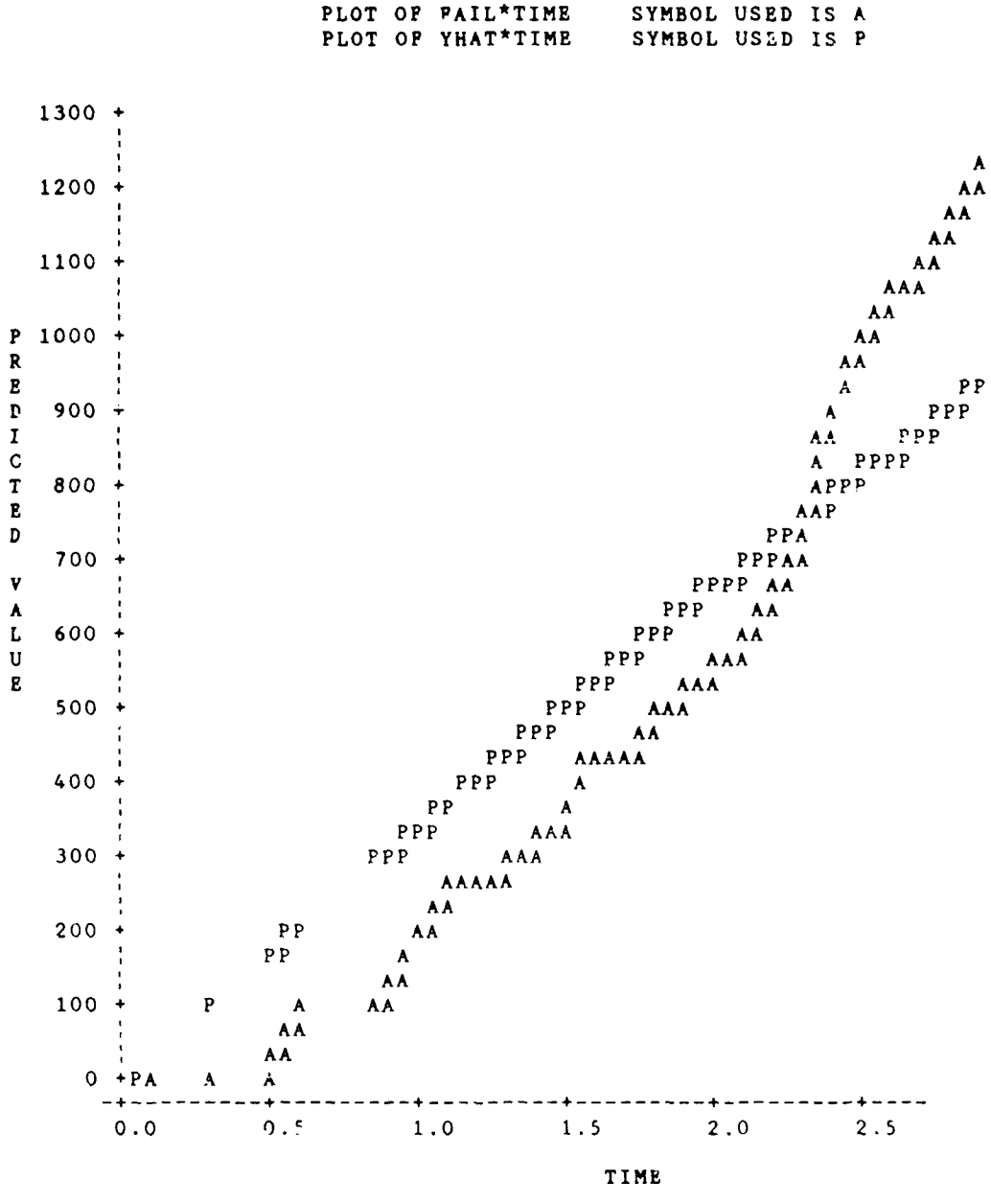


Figure 16: Model versus Actual for APOTEC Model (Data Set #5)

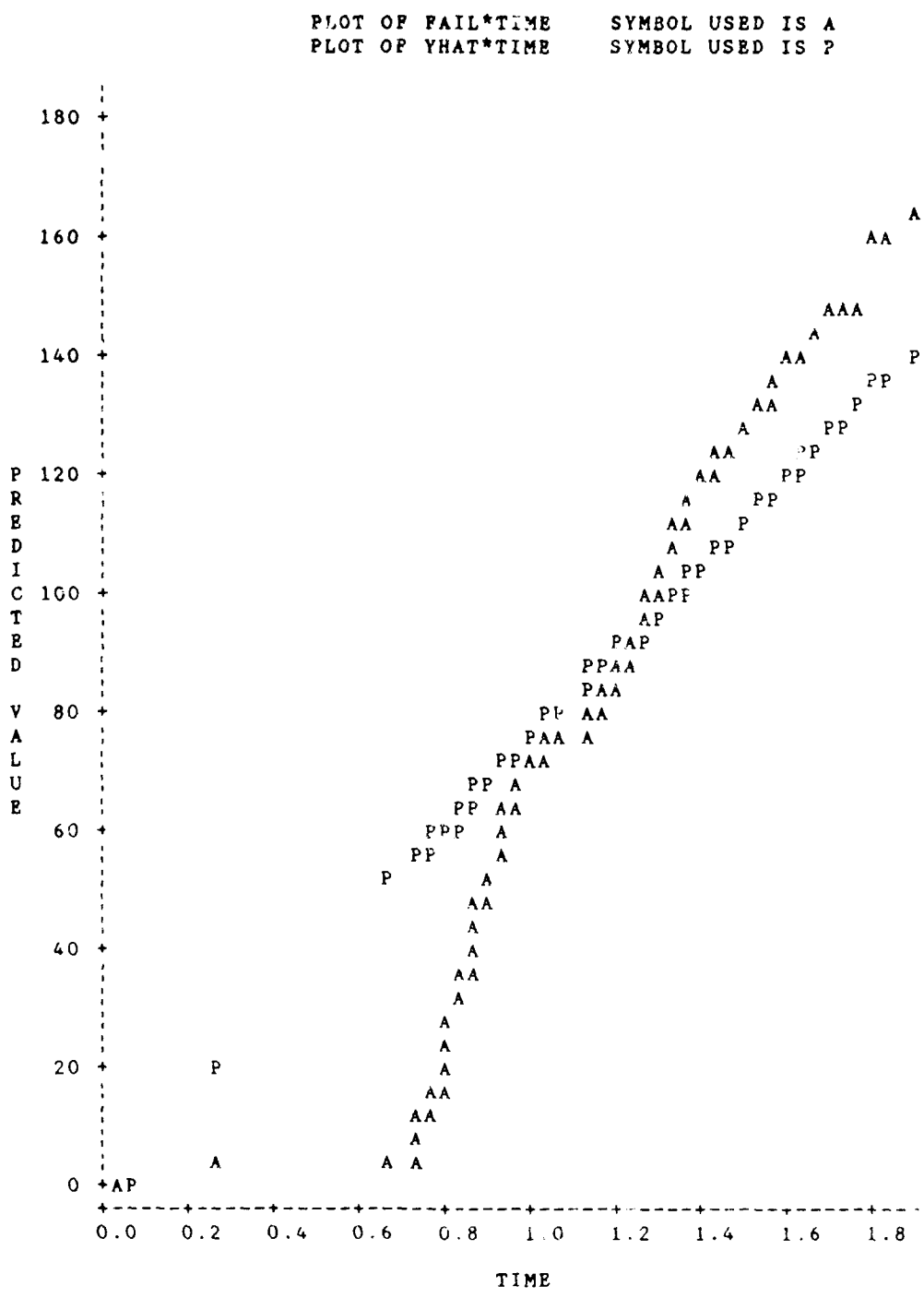


Figure 17: Model versus Actual for AFOTEC Model (Data Set #6)

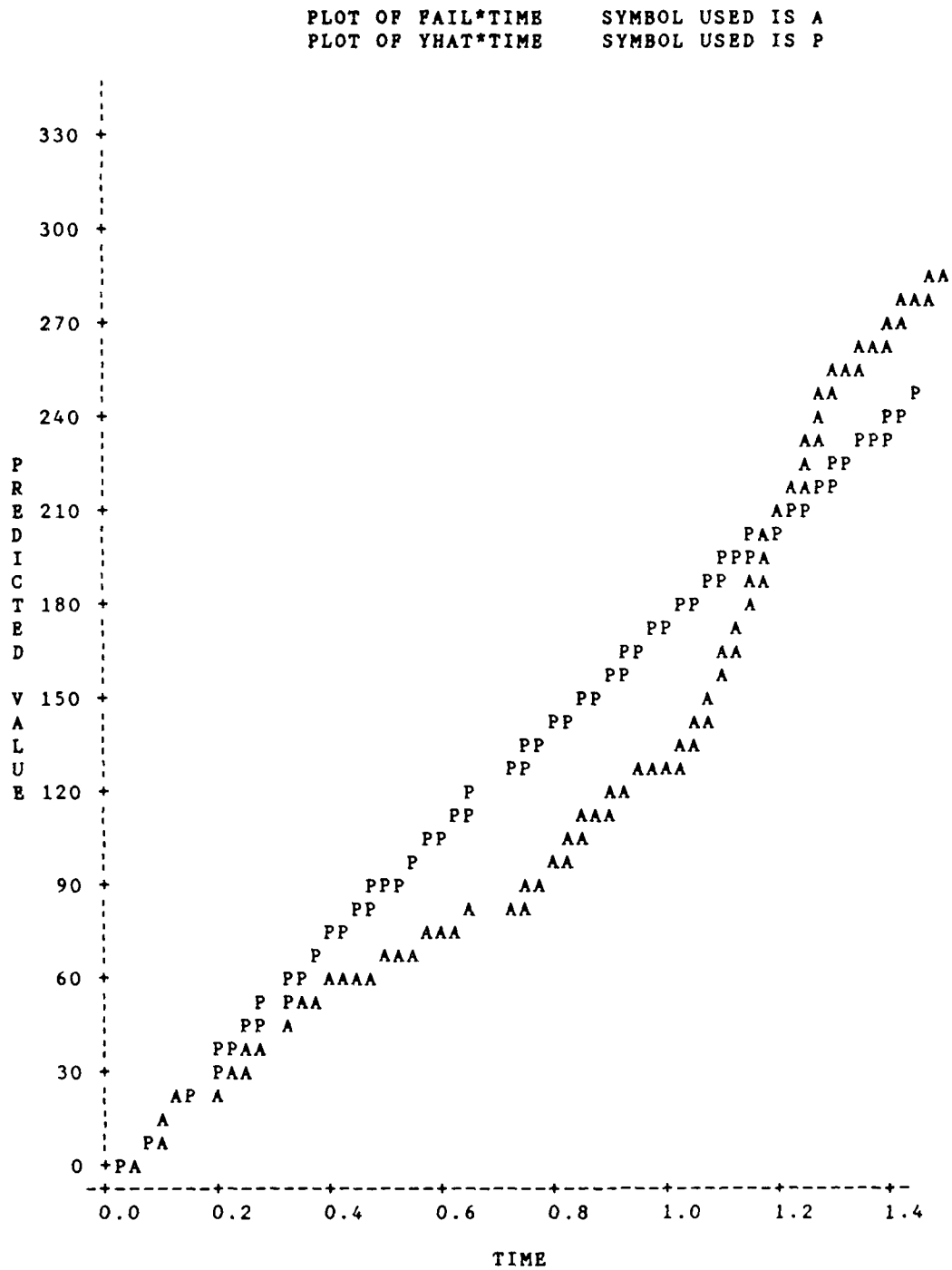


Figure 18: Model versus Actual for Model A (Data Set #1)

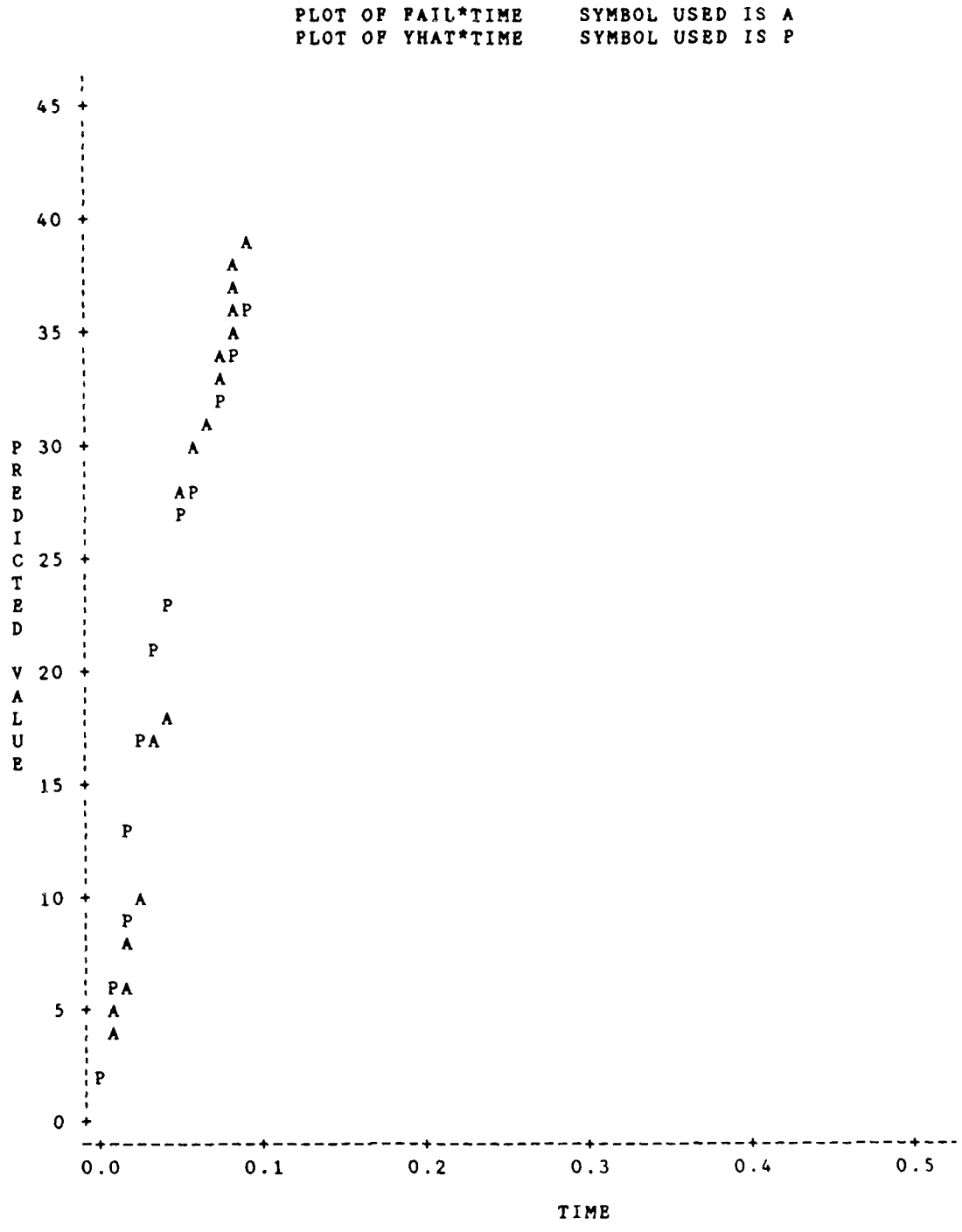


Figure 19: Model versus Actual for Model A (Data Set #2)

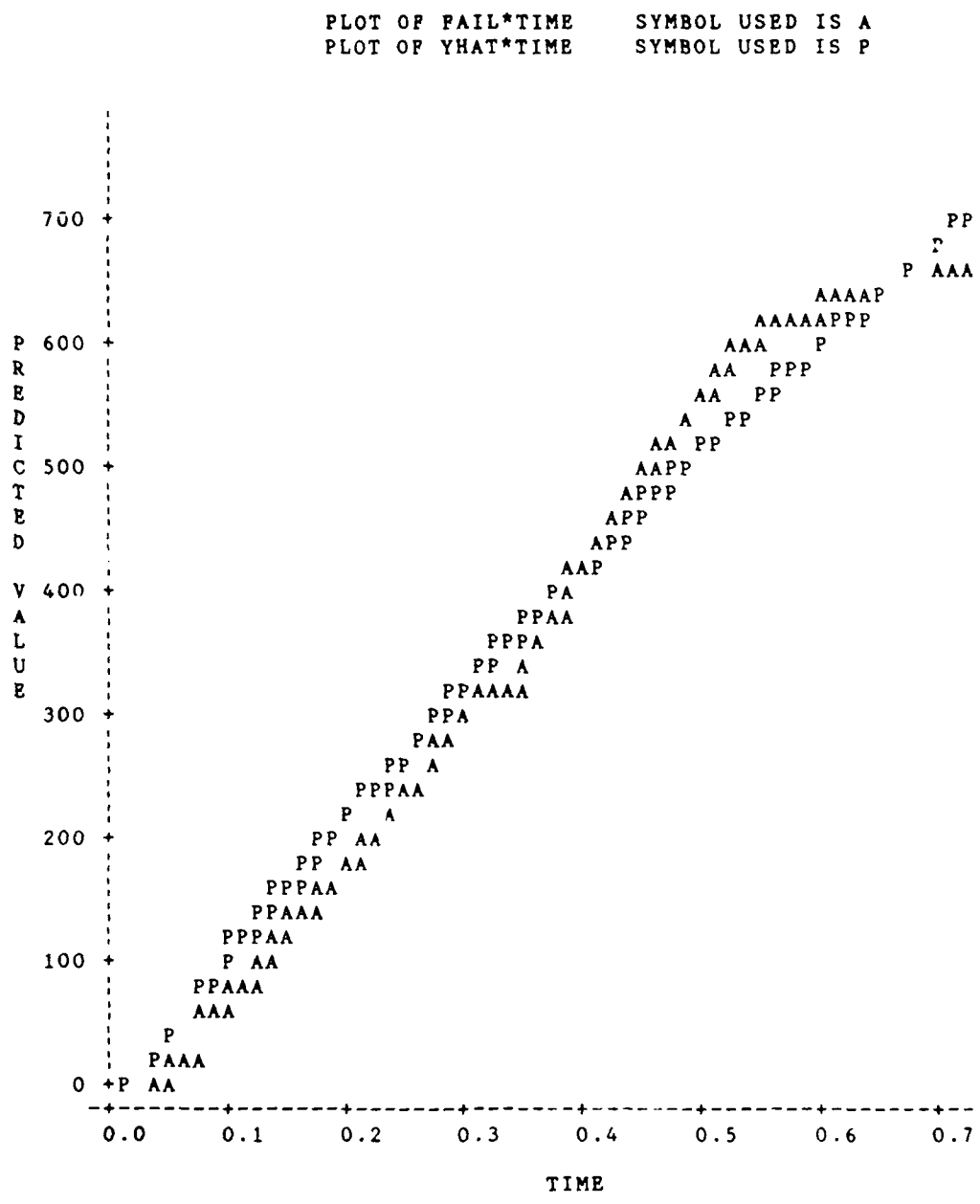


Figure 20: Model versus Actual for Model A (Data Set #3)

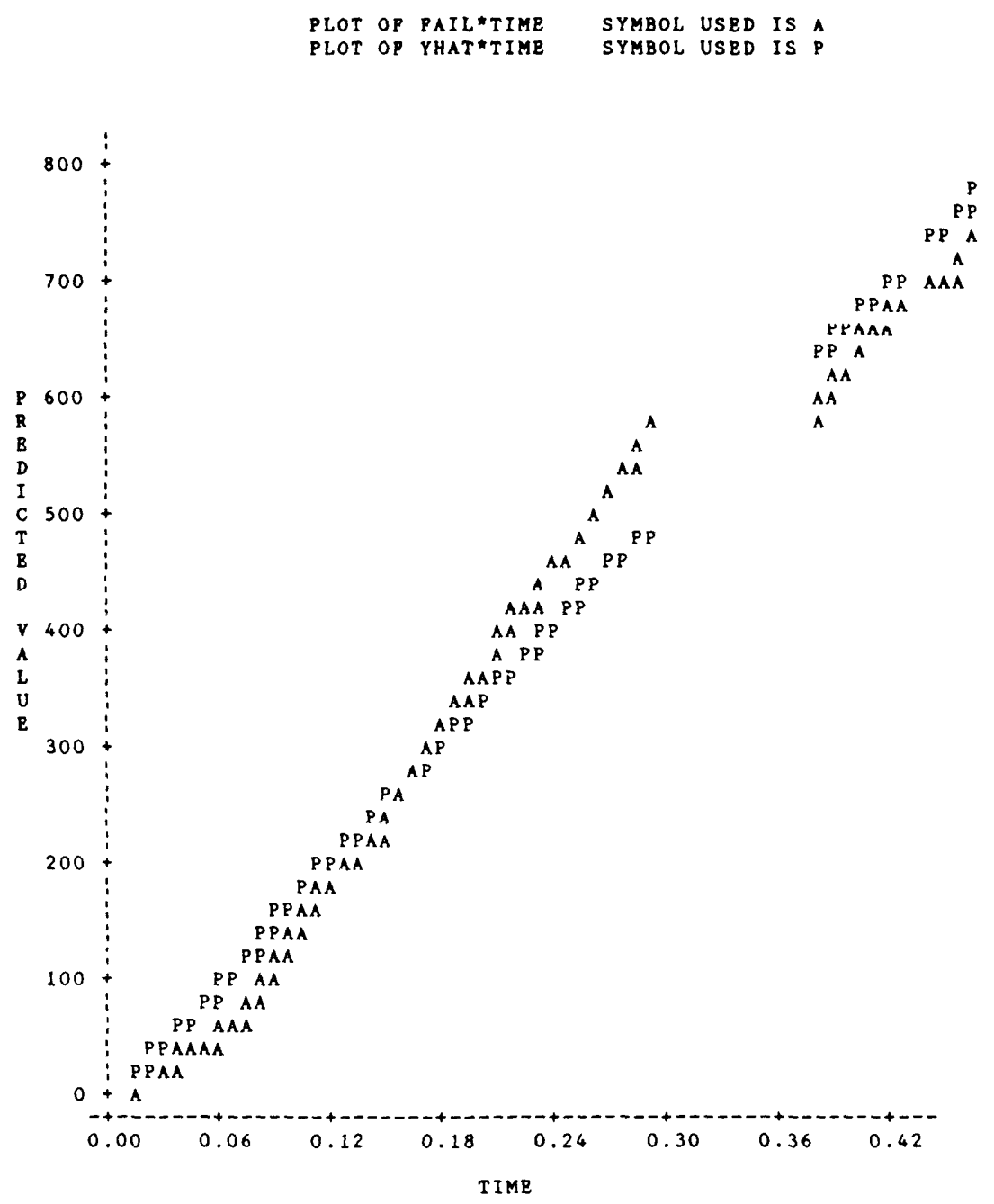


Figure 21: Model versus Actual for Model A (Data Set #4)

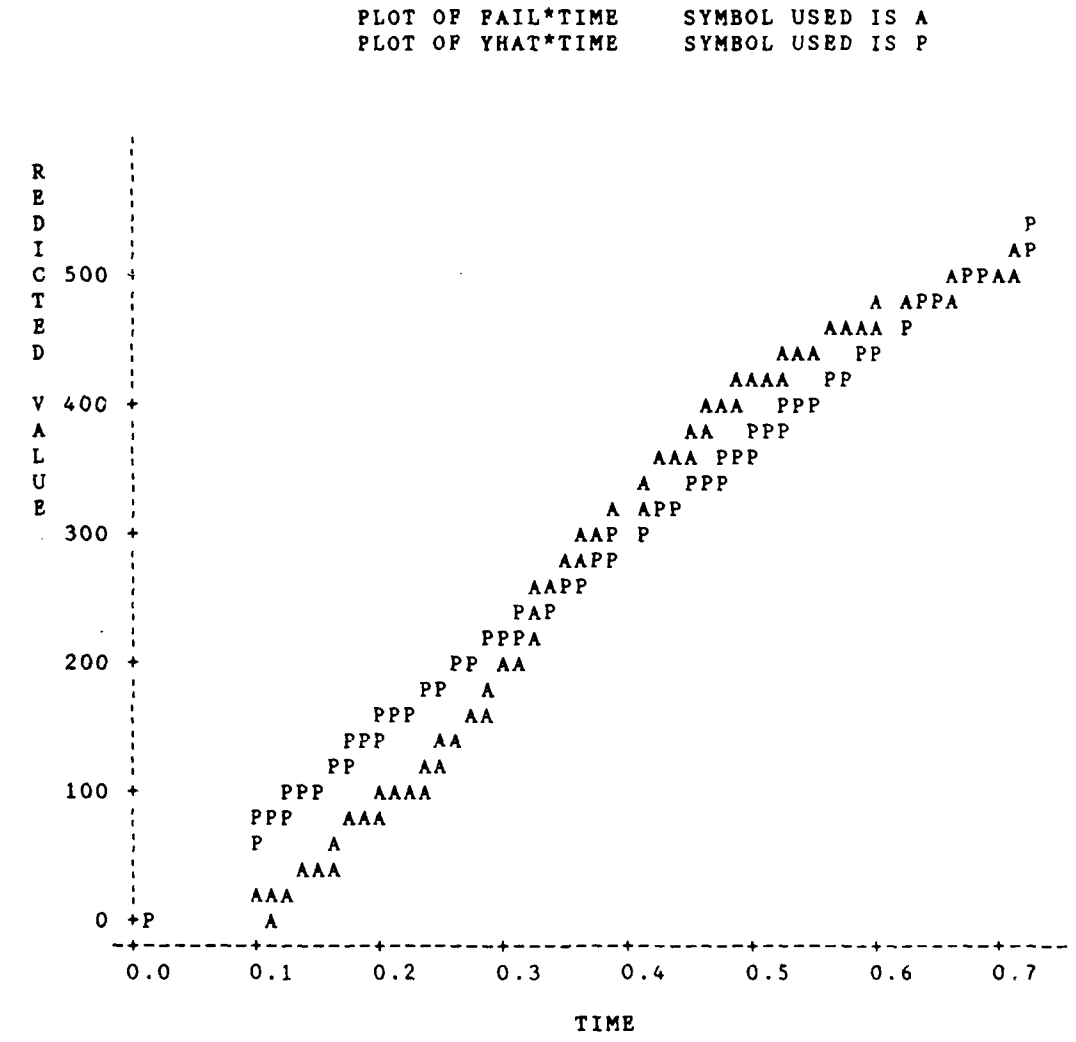


Figure 22: Model versus Actual for Model A (Data Set #5)

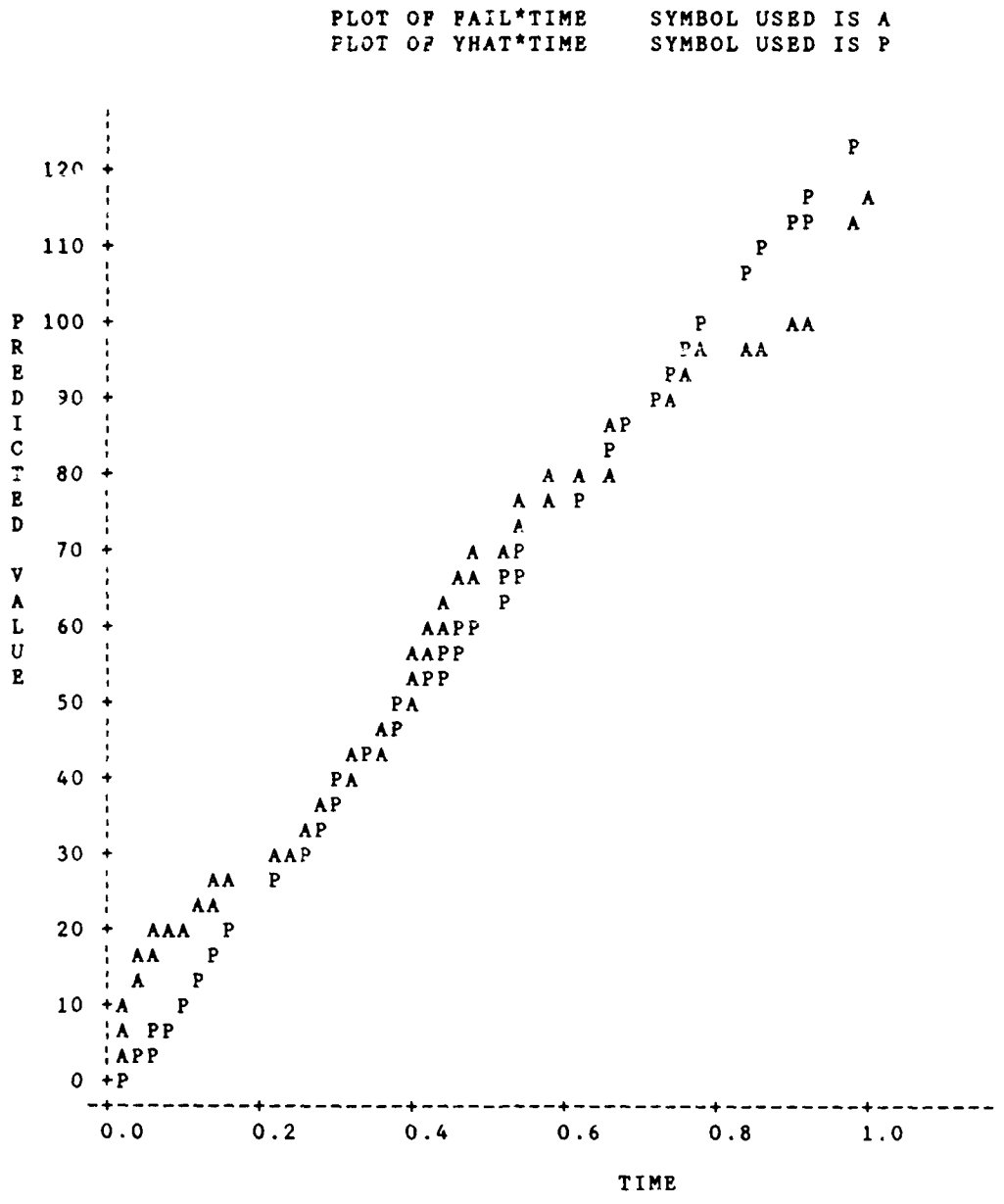


Figure 23: Model versus Actual for Model A (Data Set #6)

Appendix F: Research Data Sets

The following are data sets used in conducting the research discussed in this document. The data found below are in the format: Date(YYYYMMDD), and the next number is the cumulative number of faults detected by that date.

DATA SET #1 (Space System)

19860424 1	19870317 84	19870828 141
19860514 3	19870324 85	19870831 142
19860530 4	19870327 86	19870902 144
19860606 5	19870407 88	19870908 145
19860715 6	19870408 90	19870909 146
19860905 11	19870409 91	19870914 147
19860915 16	19870413 93	19870916 149
19860916 17	19870420 94	19870917 150
19860922 18	19870429 95	19870920 151
19860930 20	19870430 96	19870921 153
19861014 24	19870503 98	19870922 154
19861016 32	19870505 100	19870924 155
19861023 35	19870527 101	19870925 158
19861103 38	19870604 102	19870926 159
19861117 39	19870612 103	19870930 161
19861119 42	19870615 104	19871001 163
19861120 43	19870616 105	19871002 164
19861126 44	19870617 106	19871005 165
19861201 45	19870618 107	19871006 167
19861204 47	19870619 108	19871007 168
19861209 50	19870622 110	19871008 169
19861210 51	19870624 111	19871010 170
19861215 56	19870625 114	19871012 171
19861218 58	19870629 116	19871013 172
19861231 59	19870702 117	19871014 174
19870102 60	19870706 119	19871015 175
19870105 64	19870707 122	19871016 177
19870107 65	19870713 123	19871017 179
19870108 66	19870715 126	19871020 183
19870112 70	19870718 127	19871021 185
19870114 71	19870722 128	19871022 187
19870121 72	19870728 130	19871023 190
19870203 74	19870730 131	19871025 191
19870206 75	19870801 132	19871026 192
19870211 76	19870804 133	19871028 195
19870217 77	19870805 134	19871029 196
19870224 78	19870806 136	19871030 197
19870303 79	19870807 138	19871102 199
19870309 80	19870810 139	19871104 200
19870312 82	19870821 140	19871105 201

19871107 202
19871109 203
19871110 204
19871111 205
19871112 214
19871113 215
19871114 217
19871115 218
19871116 219
19871117 221
19871118 223
19871120 224
19871122 225
19871125 229
19871128 230
19871130 232
19871207 237
19871208 240
19871209 245
19871211 248
19871212 249
19871214 255
19871215 260
19871216 263
19871217 264
19871221 265
19871222 267
19871224 268
19880104 270
19880108 272
19880109 273
19880114 274
19880115 275
19880117 276
19880125 277
19880126 279
19880129 282
19880202 283
19880203 284
19880204 285
19880205 286
19880208 287
19880210 288
19880211 290
19880215 291
19880217 295
19880222 296
19880227 297
19880229 298
19880301 299
19880307 300
19880308 301
19880309 302
19880315 303
19880317 308
19880320 309
19880322 312
19880323 313
19880325 314
19880329 315
19880331 316
19880404 317
19880406 318
19880408 320
19880409 321
19880413 322
19880418 324
19880419 325
19880421 326
19880425 327
19880426 329
19880428 330
19880503 331
19880504 332
19880506 333
19880511 335
19880513 336

DATA SET #2 (Aircraft System)

19870827	2
19870828	4
19870829	5
19870831	6
19870902	8
19870905	10
19870908	17
19870910	18
19870914	28
19870916	30
19870919	31
19870921	33
19870922	34
19870924	37
19870925	38
19880328	40

DATA SET #3 (Communications System)

19870129 3	19870901 104	19871204 343
19870130 5	19870910 105	19871207 350
19870202 9	19870911 106	19871208 354
19870203 16	19870916 108	19871209 360
19870204 21	19870918 115	19871210 362
19870205 22	19870923 118	19871211 376
19870206 23	19870924 121	19871214 380
19870209 25	19870925 124	19871215 385
19870210 28	19870928 127	19871216 394
19870216 30	19870929 152	19871217 399
19870217 32	19870930 156	19871218 404
19870218 33	19871001 159	19871221 412
19870219 38	19871005 165	19871222 415
19870225 39	19871006 168	19871223 419
19870226 40	19871007 170	19871228 420
19870302 41	19871008 173	19871229 422
19870305 42	19871009 175	19871230 426
19870306 45	19871012 177	19880104 429
19870313 46	19871013 187	19880105 436
19870319 47	19871014 190	19880106 442
19870323 48	19871015 196	19880107 448
19870331 49	19871016 203	19880109 459
19870420 50	19871019 205	19880110 464
19870514 51	19871020 211	19880111 471
19870527 52	19871021 217	19880112 473
19870603 58	19871023 226	19880113 476
19870610 62	19871026 233	19880114 481
19870615 63	19871027 236	19880115 486
19870619 64	19871029 243	19880118 489
19870624 65	19871102 249	19880119 496
19870629 66	19871103 253	19880120 504
19870702 67	19871104 260	19880121 515
19870713 68	19871105 263	19880122 521
19870714 72	19871106 266	19880124 524
19870716 74	19871109 268	19880125 527
19870720 77	19871110 272	19880126 533
19870722 82	19871111 277	19880127 541
19870723 83	19871112 284	19880128 543
19870724 85	19871113 287	19880129 547
19870728 89	19871117 288	19880201 554
19870729 91	19871118 296	19880202 557
19870730 92	19871119 297	19880203 565
19870805 95	19871120 308	19880204 568
19870810 96	19871123 315	19880205 574
19870812 97	19871124 320	19880208 581
19870813 98	19871125 325	19880209 584
19870817 101	19871130 333	19880210 598
19870824 102	19871202 338	19880211 603
19870827 103	19871203 339	19880212 605

19880215 609
19880216 611
19880218 621
19880219 623
19880221 625
19880222 628
19880223 631
19880224 633
19880225 645
19880226 648
19880229 651
19880301 654
19880302 658
19880303 664
19880304 670
19880307 674
19880308 676
19880309 682
19880310 688
19880311 692
19880314 696
19880315 700
19880316 701
19880317 704
19880318 710
19880322 713
19880323 715
19880325 721
19880329 722
19880330 724
19880404 726
19880405 727
19880407 730
19880411 732
19880413 735
19880414 736
19880415 741
19880418 743
19880422 746
19880425 747
19880502 753
19880512 754
19880513 756
19880516 757
19880517 760
19880519 761
19880520 763
19880524 764
19880525 765
19880527 766
19880606 767
19880607 769
19880608 770

DATA SET #4 (Communications System)

19880328 4	19880627 121	19880829 367
19880330 9	19880628 125	19880830 384
19880406 11	19880629 130	19880831 386
19880411 13	19880701 133	19880901 390
19880413 16	19880705 136	19880902 391
19880414 19	19880706 138	19880904 392
19880415 21	19880708 144	19880905 394
19880418 22	19880709 145	19880906 402
19880419 24	19880711 148	19880907 410
19880420 25	19880712 149	19880908 414
19880421 28	19880713 156	19880909 421
19880422 30	19880714 160	19880910 423
19880426 31	19880715 162	19880911 428
19880427 36	19880719 173	19880912 438
19880429 39	19880720 177	19880913 441
19880501 40	19880721 187	19880914 450
19880503 41	19880722 192	19880915 461
19880504 42	19880723 196	19880916 474
19880505 45	19880724 197	19880917 483
19880506 47	19880725 204	19880919 494
19880509 50	19880726 213	19880920 498
19880510 56	19880727 217	19880921 506
19880512 57	19880728 224	19880922 521
19880516 58	19880729 227	19880923 526
19880517 59	19880801 228	19880926 531
19880518 60	19880802 233	19880927 539
19880519 62	19880803 237	19880928 549
19880524 63	19880804 239	19880929 554
19880526 66	19880805 241	19881002 555
19880527 69	19880808 245	19881003 565
19880602 73	19880809 249	19881004 583
19880603 74	19880810 255	19881005 590
19880606 76	19880811 257	19881006 600
19880607 77	19880812 264	19881007 615
19880608 81	19880813 266	19881008 616
19880609 83	19880815 269	19881010 621
19880610 85	19880816 273	19881011 626
19880613 86	19880817 284	19881012 643
19880614 91	19880818 294	19881013 647
19880615 92	19880819 297	19881014 659
19880616 93	19880820 307	19881015 661
19880617 94	19880821 309	19881017 663
19880618 96	19880822 318	19881018 668
19880620 99	19880823 322	19881019 674
19880621 104	19880824 328	19881020 680
19880622 108	19880825 335	19881021 688
19880623 110	19880826 343	19881022 692
19880624 112	19880827 354	19881023 693
19880625 115	19880828 361	19881024 704

19881025 710
19881026 722
19881027 734
19881028 740
19881029 742
19881031 765
19881101 767
19881102 775
19881205 776
19881206 789
19881207 794
19881208 799
19881209 815
19881212 824
19881213 841
19881214 846
19881215 857
19881216 860
19881217 862
19881218 863
19881219 877
19881220 882
19881221 889
19881222 894
19881227 895
19881228 904
19881230 905
19890103 909
19890104 920
19890105 931
19890106 938
19890107 947
19890108 948
19890109 959
19890110 968
19890111 986
19890112 991
19890113 1000
19890114 1002
19890116 1020
19890117 1027
19890118 1036
19890119 1046
19890120 1053
19890121 1054
19890122 1055
19890123 1058
19890124 1066
19890125 1074
19890126 1079
19890127 1085
19890128 1086
19890129 1089
19890130 1093
19890131 1100

DATA SET #5 (Space System)

19860116 1	19861209 161	19870424 287
19860415 2	19861210 162	19870425 293
19860623 4	19861212 164	19870427 294
19860624 7	19861215 171	19870428 295
19860625 11	19861216 173	19870430 297
19860626 12	19861217 175	19870505 299
19860630 15	19861218 180	19870508 300
19860701 16	19861222 186	19870511 302
19860702 17	19861227 188	19870512 303
19860707 18	19861229 189	19870513 304
19860710 21	19861230 190	19870514 306
19860711 27	19861231 195	19870519 310
19860713 28	19870107 196	19870520 311
19860714 31	19870108 199	19870521 313
19860715 36	19870109 206	19870527 314
19860716 41	19870112 210	19870529 319
19860717 50	19870113 212	19870530 320
19860718 51	19870114 215	19870602 322
19860721 55	19870115 225	19870603 323
19860722 59	19870116 226	19870605 327
19860723 63	19870117 229	19870606 328
19860724 67	19870119 231	19870609 330
19860725 68	19870120 235	19870610 332
19860726 72	19870121 236	19870611 334
19860728 74	19870122 237	19870615 335
19860729 78	19870123 242	19870616 336
19860730 79	19870127 246	19870617 341
19860731 80	19870128 248	19870618 343
19860801 81	19870129 249	19870619 344
19860812 84	19870130 253	19870622 346
19861106 85	19870202 256	19870624 349
19861107 86	19870204 261	19870625 354
19861110 89	19870206 262	19870629 361
19861112 90	19870210 263	19870630 362
19861117 92	19870225 264	19870701 364
19861118 94	19870227 265	19870702 374
19861119 96	19870303 266	19870703 376
19861120 99	19870310 268	19870706 380
19861121 100	19870320 269	19870707 382
19861124 121	19870323 271	19870708 384
19861125 127	19870327 272	19870709 394
19861126 129	19870328 273	19870710 402
19861201 133	19870330 274	19870713 415
19861202 136	19870401 275	19870714 418
19861203 139	19870414 276	19870715 419
19861204 145	19870415 277	19870716 422
19861205 146	19870417 278	19870717 424
19861207 149	19870418 280	19870720 425
19861208 153	19870421 286	19870721 427

19870722 428	19880106 552	19880325 696
19870724 429	19880107 553	19880328 698
19870727 430	19880108 554	19880329 700
19870812 432	19880109 555	19880330 701
19870813 433	19880110 556	19880331 702
19870815 434	19880112 558	19880402 703
19870825 435	19880113 560	19880404 705
19870904 436	19880114 561	19880405 710
19870910 438	19880115 564	19880407 716
19870917 441	19880116 567	19880408 722
19870918 446	19880117 568	19880410 723
19870921 447	19880119 570	19880411 731
19870922 455	19880122 575	19880412 733
19870923 456	19880125 577	19880413 740
19870923 460	19880126 578	19880414 744
19870928 462	19880127 579	19880415 747
19870929 466	19880128 581	19880418 752
19870930 470	19880129 582	19880419 755
19871001 471	19880130 585	19880420 757
19871005 473	19880201 588	19880422 759
19871006 476	19880202 589	19880423 764
19871007 479	19880203 591	19880424 765
19871009 481	19880204 592	19880425 772
19871016 482	19880205 593	19880426 782
19871019 486	19880208 596	19880427 796
19871026 488	19880211 598	19880428 799
19871027 489	19880212 600	19880429 801
19871028 490	19880216 602	19880430 802
19871029 494	19880217 607	19880502 808
19871031 495	19880218 610	19880503 816
19871103 497	19880219 613	19880504 821
19871109 503	19880222 614	19880505 827
19871111 511	19880223 620	19880506 829
19871113 516	19880224 625	19880507 831
19871117 520	19880225 628	19880508 833
19871122 521	19880226 629	19880509 837
19871125 523	19880301 631	19880510 850
19871130 527	19880302 633	19880511 860
19871201 531	19880303 636	19880512 863
19871207 532	19880308 643	19880513 864
19871208 533	19880309 646	19880514 865
19871210 534	19880311 649	19880516 871
19871215 535	19880312 650	19880517 875
19871216 537	19880314 672	19880518 879
19871217 541	19880315 674	19880520 886
19871219 542	19880316 676	19880521 888
19871221 543	19880317 677	19880523 889
19871222 544	19880318 678	19880524 896
19871230 545	19880321 683	19880525 903
19871231 546	19880322 687	19880526 908
19880104 550	19880323 689	19880527 909
19880105 551	19880324 692	19880530 913

19880531 918
19880601 923
19880602 925
19880607 926
19880608 933
19880609 937
19880610 943
19880611 948
19880613 951
19880614 953
19880615 956
19880616 958
19880617 962
19880618 964
19880620 966
19880621 968
19880622 971
19880623 976
19880624 984
19880627 986
19880628 990
19880629 991
19880630 996
19880701 998
19880705 1000
19880706 1003
19880707 1005
19880708 1013
19880710 1014
19880711 1016
19880712 1020
19880713 1022
19880715 1024
19880717 1025
19880718 1029
19880719 1030
19880720 1033
19880721 1034
19880722 1035
19880724 1039
19880725 1042
19880726 1044
19880727 1049
19880802 1050
19880804 1053
19880805 1057
19880809 1058
19880810 1061
19880815 1063
19880816 1064
19880817 1066
19880818 1070
19880825 1071
19880831 1075
19880901 1076
19880902 1078
19880905 1086
19880906 1088
19880907 1090
19880908 1091
19880912 1092
19880913 1093
19880914 1094
19880915 1095
19880916 1098
19880918 1099
19880919 1100
19880921 1101
19880922 1103
19880924 1104
19880927 1109
19880928 1111
19880929 1119
19880930 1123
19881003 1126
19881005 1127
19881006 1128
19881007 1130
19881011 1141
19881013 1145
19881014 1146
19881017 1147
19881018 1151
19881020 1154
19881021 1162
19881022 1163
19881023 1164
19881024 1168
19881025 1169
19881026 1173
19881027 1179
19881028 1182
19881029 1185
19881101 1186
19881102 1187
19881103 1190
19881104 1193
19881107 1196
19881108 1199
19881110 1200
19881114 1204
19881115 1210
19881116 1213
19881117 1218
19881118 1221

DATA SET #6 (Space System)

19870112 1	19880114 73	19880724 131
19870409 2	19880115 74	19880726 135
19870902 4	19880117 75	19880729 137
19870920 5	19880125 76	19880805 138
19870922 6	19880215 77	19880817 139
19870924 7	19880217 79	19880823 140
19870925 9	19880222 80	19880826 143
19870926 10	19880227 81	19880831 144
19870930 11	19880229 82	19880902 145
19871001 13	19880301 83	19880911 146
19871007 14	19880307 84	19880928 147
19871008 15	19880309 85	19881009 148
19871012 16	19880315 86	19881022 159
19871013 17	19880320 87	19881026 160
19871015 18	19880322 90	19881029 161
19871016 19	19880323 91	19881120 163
19871017 21	19880325 92	19881123 164
19871020 24	19880331 93	19881130 165
19871022 26	19880404 94	19881215 166
19871023 29	19880406 95	
19871025 30	19880408 97	
19871028 33	19880411 98	
19871030 34	19880418 99	
19871102 36	19880418 100	
19871107 37	19880419 101	
19871109 38	19880421 102	
19871110 39	19880425 106	
19871111 40	19880426 107	
19871112 41	19880427 108	
19871113 42	19880428 109	
19871114 44	19880504 110	
19871115 45	19880506 112	
19871117 46	19880508 113	
19871120 47	19880510 114	
19871122 48	19880511 116	
19871125 49	19880516 117	
19871128 50	19880521 118	
19871207 54	19880523 119	
19871208 56	19880602 120	
19871209 60	19880605 121	
19871211 63	19880609 123	
19871214 65	19880611 124	
19871216 67	19880614 125	
19871217 68	19880625 126	
19871222 69	19880628 127	
19871224 70	19880629 128	
19880104 71	19880630 129	
19880109 72	19880711 130	

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The purpose of this thesis was to determine the validity of a software reliability estimation model proposed by the Air Force Operational Test and Evaluation Center (AFOTEC). During the last forty years of the computer era, the demand for software has been growing at a rate of twelve percent per year; and about fifty percent of the total life cycle cost of a software system is attributed to software maintenance. It has also been shown that the cost of fixing a software fault increases dramatically as the life cycle progresses. It was statistics like those discussed above that prompted this research.

The research had these specific objectives: the first was ascertaining the soundness of the model's intrinsic logic. The second objective was to run the model with actual failure data to measure the validity and correlation of the data with the model. The final objective was to determine the assumptions required to operate the model.

The study found the AFOTEC Model to be invalid; however, improvements and assumptions could be easily applied to make the model a valid tool for estimating software reliability. Two improvements were proposed for the AFOTEC Model. First, the model should operate with the assumption that the data used in the model should be data obtained after software testing has reached a steady state. The second recommendation was to modify the AFOTEC Model to emulate both the start-up phase and the steady state phase of testing.